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TEGMINAL STRUCTURE OF THE PENNSYLVANIAN-PERMIAN CRINOID *DELOCRINUS*

RAYMOND C. MOORE AND HARRELL L. STRIMPLE

Received December 9, 1940; published April 30, 1941

Abstract.—A large majority of the known Upper Carboniferous and Permian crinoids are inadunates, characterized by elevation of the tegmen in the form of an anal tube or sac. The structure of this sac is varied in form, and in many genera its character is well known. In *Delocrinus*, however, although it is the most common and characteristic of all these crinoids, the nature of the tegmen has not previously been recorded. Specimens representing three species of *Delocrinus* have been found that show a strongly elevated cylindrical sac bearing a terminal spine. The plates of the sac are very thin, and not joined firmly together; hence the sac is not normally preserved. A new species of *Delocrinus* from Lower Permian beds of central Kansas is described.

INTRODUCTION

The most common and characteristic crinoids in Pennsylvanian and Permian rocks of North America belong to the genus *Delocrinus* Miller and Gurley. Relative abundance is indicated both by the number of described species and number of individual specimens. Excluding species that are now referred to closely related genera such as *Paradelocrinus* Moore and Plummer (1938, p. 294; 1940, p. 317) and *Endelocrinus* Moore and Plummer (1940, p. 296), there are some thirty described American forms of *Delocrinus* as well as numerous undescribed species. Wanner (1916, 1924) has described a dozen species and varieties of *Delocrinus* from the Permian rocks of Timor, though it is clear that some of these should be transferred to other genera. Approximately 1000 specimens of *Delocrinus*, consisting mostly of dorsal cups but including numerous complete crowns, have been available for our study.

Characteristics of Delocrinus.—The dorsal cup of *Delocrinus* has a low truncate bowl-shaped form, and it is characterized especially by the presence of a deep basal concavity. The outline in

views from above or below is circular to subpentagonal. The cup is composed of 16 firmly united plates, consisting of 5 infrabasals, 5 basals, 5 radials, and an anal plate. The infrabasals, lying next to the stem, are entirely hidden within the basal concavity, and are not visible in side view of the cup. They flare strongly downward. The midportion of the basal plates are tangent to the basal plane of the cup, proximal parts being included in the central concavity and distal parts rising to about mid-height of the cup. The radial plates are pentagonal in outline, about twice as wide as long, and they curve evenly upward to the summit plane of the cup. The anal plate normally rests on the truncated tip of the posterior basal, separating the posterior radials, but in a few specimens it does not reach downward to the basal circlet, and in this case does not completely separate the posterior radials.

The first plate in each of the five rays of *Delocrinus* is a stout axillary brachial that in some cases is prolonged laterally as a spine. The two arms that follow each of these plates do not branch further, and accordingly the crown has ten arms in all. These arms above the first or second secundibrach are composed of biserially arranged interlocking wedge-shaped segments. The exterior of the arms is gently rounded and there is a sharp angulation between the exterior and the side of the arms. Numerous long slender pinnules are attached to the arms but with the arms in normal closely appressed position the pinnules are not visible from the exterior. The stem of *Delocrinus* is moderately slender and the segments are circular in outline.

Geologic distribution of Delocrinus.—No Mississippian (Lower Carboniferous) species of *Delocrinus* have been observed, but typical representatives appear in lower Pennsylvanian (Upper Carboniferous) Morrow beds, of the Mid-Continent region. Increased numbers of *Delocrinus* appear in strata of Des Moines age (lower middle Pennsylvanian) but greatest abundance and variety of forms belonging to this genus is found in rocks of Missouri age (upper middle Pennsylvanian). The Virgil (upper Pennsylvanian) and Lower Permian beds show a marked decline in the number of species and individuals belonging to *Delocrinus*, but because of still greater reduction in other kinds of crinoids known,

their relative prominence in these horizons is increased rather than reduced. Representatives of *Delocrinus* are a minor rather than a major element in the crinoid fauna of Timor, however.

TEGMINAL STRUCTURE OF DELOCRINUS

Delocrinus granulosus (*Pl. 1, figs. 1–3*).—An incomplete crown of *Delocrinus granulosus* Moore and Plummer (1940, p. 265) from a lower Atoka horizon in northeastern Oklahoma (see Newell, 1937, p. 27) is of special interest because it reveals the presence of an anal sac, and because it shows a distinctive form of the arms, not preserved in the types from Texas. The specimen is preserved as an external and internal mold in fine calcareous sandstone, and although none of the original substance of the crinoid remains, the undistorted form of the anal sac and its structure are indicated. The posterior side of the cup, including the anal plate, is not shown but the distinctive form of the basal plates, presence of a strongly marked basal concavity in the cup and characters of the arms do not leave doubt as to its belonging to *Delocrinus*.

The crown has a somewhat pyriform outline owing to the prominent bulge of the arms somewhat above their midheight. The plates of the dorsal cup are somewhat displaced, but there are clearly defined molds of three radials, two basals, the infrabasal circlet and the stem impression. The radials and other plates exhibit the typical form and decoration of *D. granulosus* and the dorsal cup is about the same in size as the holotype of this species. The external mold shows only the anterior side of the crown, but the interior mold is complete except for a small part of the cup. The axillary first primibrachs, which are about twice as wide as long, bear granules and tubercles like the plates of the dorsal cup. Their rounded surface rises to a point of chief prominence that is centrally located on the distal margin, but this is not produced in a spine. The first secundibrachs are quadrangular in outline and about half as long as the primibrachs, but the following brachials are all biserially arranged, the segments in the lower part of the arms being notably smaller than those at midheight. A series of nodes occurs along the middle of each arm except in the distal region, the largest size and greatest prominence of these

nodes being attained at mid-height of the arms. A longitudinal series of less prominent nodes marks each of the two flanks of the outer face of the arms, but these rows do not persist beyond mid-height of the crown. Unlike most other species of *Delocrinus*, the outer surface of the arms appears strongly carinate instead of flattened and a profile of any one of the arms calls attention to the rounded serrations produced by the central nodes and to the strongly marked bulge of the arms just above their mid-height. The exterior of all arm segments is ornamented by closely spaced granules. A sharp angle separates the outer face of the arms from the sides, which show strongly marked horizontal grooves and ridges where the arms interlock.

The anal sac has a subcylindrical form with elliptical cross-section and is approximately uniform throughout its height. The maximum diameter of the sac is a little less than the width of one of the arms. It is formed by very thin plates that are arranged in about ten vertical series, plates of adjoined rows alternating in position. Each plate bears a low keel that is aligned with keels of other plates in the vertical series to make somewhat flexuous, slightly serrate vertical ridges. At the junction of some plates there are pores or slits, probably respiratory in function. Except for presence of a terminal, vertically directed spine, the top of the sac is evenly rounded, not expanded. The total height of the sac is about 30 mm., which is about three-fourths of the height of the arms. The height of the crown is 50 mm. and its greatest width is about 30 mm.

Identification of the crinoid that has been described is made with little hesitation owing to the distinctive decoration of the dorsal cup. Fine granulose markings combined with rounded tubercles and occurrence of moderately depressed sutures between the plates of the cup are seen, however, in *Delocrinus parinodosarius* Strimple (1940, p. 6) described from the Wewoka formation near Holdenville, Oklahoma. Comparison of the specimen that shows arms and sac with the types of *D. granulosus* and *D. parinodosarius* calls attention to the much smaller size and more delicate ornamentation of Strimple's species.

The sac-bearing specimen was collected by Norman D. Newell

from the Coody Creek sandstone member of the Atoka formation (lower Des Moines), Pennsylvanian, NW¼, NW¼, NW¼, sec. 33, T. 15 N., R. 20 E., Muskogee County, Oklahoma. The specimen belongs in the collection of the Oklahoma Geological Survey.

Delocrinus megalobrachius (*Pl. 1, figs. 5, 6*).—In 1899 Beede (p. 124, pl. 32, figs. 1a–b) described a new species of crinoid from the "Upper Coal Measures, horizon of Osage coal, Topeka, Kansas." The holotype, and only known example of this species, insofar as records go, is a well preserved crown in which only the tips of the arms are broken away. The species was named *Erisocrinus megalobrachius*, and without change, the species was redescribed by Beede in 1900 (p. 37, pl. 7, figs. 1a–b). The exact locality from which this fossil came is not known, but in terms of present stratigraphic nomenclature, there is no doubt as to its occurrence in a part of the Howard limestone overlying the Nodaway coal.

Examination of the holotype, which is in the collection at the University of Kansas, called attention to occurrence of a spine-like plate that was barely visible within the circle of arms along the fractured upper edge of the crown. It seemed possible that this plate was the terminal spine of an anal sac. Careful effort was made to study the structure inside the circle of arms, and fortunately it proved possible to remove part of the arms without damaging the specimen. This showed definitely the existence of an anal sac, the plates slightly disturbed in position, but the form and structure of the sac being indicated with reasonable clearness. At the time of this discovery, the sac structure of *Delocrinus granulosus*, as already described, had been investigated, and it was supposed that the anal sac now demonstrated to be present in the type of Beede's species from the vicinity of Topeka, showed that *Erisocrinus* had an anal sac very similar to that of *Delocrinus*. This conclusion probably accords with the facts, but seemingly this determination cannot rest on study of "*Erisocrinus*" *megalobrachius*. The species is here transferred to *Delocrinus*, as indicated by the heading of this section of the paper. Reasons for this generic reassignment, and also for suppressing "*Ceriocrinus*" (equals *Delocrinus*) *harshbargeri* Beede (1902, p. 147, pl. 5,

figs. 1a–c), as a synonym of *Delocrinus megalobrachius* may be given before attention is directed to features of the anal sac in this species.

As has been found true of many type specimens of older workers on the Carboniferous crinoids, the type of *"Erisocrinus" megalobrachius* had not been carefully or completely cleaned. Study of the specimen showed that one of the distally pointed basals was longer than the others, and removal of matrix between the upper part of the radials next above this elongate basal showed the presence of an anal plate that projects downward slightly into the cup. The distance from the distal extremity of the posterior basals to the summit line of the radials in this specimen is 3 mm., the posterior radials being in contact for 2 mm. of this distance and separated by the proximally pointed anal x in the remaining 1 mm. The surface of the anal plate curves abruptly forward above the radials and attains a maximum observed width of 2 mm.

The characters of the posterior portion of the cup just described are not in themselves sufficient grounds for definite generic assignment. Occasional specimens that undoubtedly belong to *Erisocrinus* have an anal plate that extends very slightly below the summit of the radials, as in the type of *"E." megalobrachius*. The same is true of occasional specimens of *Paradelocrinus*, as in the case of the holotype of *P. dubius* (Mather) (see Moore and Plummer, 1938, p. 297). Likewise some specimens that are regarded definitely as belonging to *Delocrinus* have a perfectly symmetrical dorsal cup, the anal plate being entirely excluded from the exterior of the cup. These conclusions rest on comparative study of many specimens and indicate merely a variability that is partly inherent in individual aberrations from a norm and that is partly expression of the position of a species in regard to the widely prevalent evolutionary tendency among inadunates to press anal plates upward and outward from the cup. The deep basal concavity of *"E." megalobrachius* is a feature entirely foreign to *Erisocrinus*, narrowly and presumably properly defined, but this feature occurs in *Paradelocrinus*.

The chief reason for thinking that *"E." megalobrachius* actually belongs to *Delocrinus* rests on the conclusion that *Delocrinus*

harshbargeri Beede, which was described from the same locality and horizon as "*E.*" *megalobrachius*, is actually synonymous with this species. The holotype of *D. harshbargeri* is an almost perfect crown, and at present it is the only known representative of the species. The type specimen, which is in the collections of Washburn College at Topeka, has been loaned for study, and in every respect it is seen to be a typical representative of *Delocrinus*. At the level of the radial summits, the anal plate has a width of about 6 mm.; it extends 5 mm. downward into the cup and rests on the broadly truncated distal extremity of the posterior basal. Its form, size, and distinctive granulose ornamentation, however, are almost exactly like those of "*E.*" *megalobrachius*. The appearance of the low, short-spined primibrachs and of the arms above them is almost identical. Seemingly, the only basis for distinction is the occurrence of a few weakly marked tubercles in a discontinuous row near the upper border of the radials in *D. harshbargeri*, serving slightly to accentuate a bulge in this part of the plate. These tubercles are much less distinct on some of the radials than on others. The form of the radials in "*E.*" *megalobrachius* is the same as in form considered, including the bulge near the margin of the facet and faint tubercles can be seen on some plates but this ornamentation is certainly not as well developed as in *D. harshbargeri*. Taking account of the fact that these two crinoids were obtained from the same horizon and locality and have so many corresponding points, it is reasonable to conclude that they represent merely individual variations of a single species. They are here so treated. Following this procedure, the valid name is that of the older described form.

The terminal sac spine of *D. megalobrachius* is about 7 mm. in length, bluntly pointed (possibly broken) at the tip, and 4 mm. across at the base. The plates of the sac are disarranged in such manner that it is not possible to determine the precise manner of their disposition, but there are a few vertical rows of plates that remain joined together. The size of plates in the upper part of the sac (average width and length about 1 mm.) is noticeably smaller than that in the lower part (average width and length about 1.5 mm.), and the plates of the latter region are also some-

what thicker. Each of the rows of plates is marked by a narrow keel, more strongly defined on some plates than on others. Sutures between the rows are marked by indentations, making slit-like pores that are presumed to have been respiratory in function, but sutures between plates of the same series seem to lack these openings. The total height of the sac above the summit line of the radials is 36 mm. and the diameter of the sac, as nearly as can be judged, is 8 to 10 mm., which is about the same as the greatest width of one of the arms (7 to 8 mm.). The structure of the lower part of the sac is not determinable.

Delocrinus sp. from Bartlesville, Okla. (*Pl. 1, fig. 4*).—Two specimens of *Delocrinus* that show presence of the anal sac have been collected by the junior author from upper Missouri beds (Stanton equivalent) at a prominent hill known as The Mound, at the northwest edge of Bartlesville, Oklahoma. The specimens are somewhat crushed crowns from which some of the arms have been lost, and the dorsal cups are also distorted. The two crowns are almost exactly the same in size and in all structural features, belonging without question to the same species. Despite the fact that some 200 or more dorsal cups and crowns belonging to the species have been collected, it is not definitely identified here because study has not been given to determine satisfactorily the degree of distinctness or of possible identity as compared with described forms such as *Delocrinus craigii* (Worthen), *D. subhemisphericus* Moore and Plummer (1940, p. 258) and *D. verus* Moore and Plummer (1940, p. 282). These are smooth-surfaced forms of closely similar appearance that, although distinguished readily in the case of typical examples, require careful comparative study in order to fix the range of variations. Like investigation of other smooth delocrinids is needed but it does not bear directly on identification of the upper Missouri specimens.

The Bartlesville specimens of *Delocrinus* that show characters of the anal sac both indicate the very slender tubular nature of this structure and by partial disarrangement of the plates they show a lack of firm union of the plates. The height of the sac above the summit of the radials is about 30 mm. in each case and the diameter of the sac is little if any greater than 6 mm. The

height of the arms is about 40 mm., and accordingly, the ratio of height of sac to that of arms is the same (three-fourths) as in *D. granulosus*. The terminal spine of the sac in the specimens from Bartlesville is unusually long and sharply pointed. The plates bear faint median keels, at least in some cases, and lateral margins of plates in the middle and lower parts of the sac are indented so as to produce a crenulate appearance in some cases.

General remarks.—The description of the anal sac structure observed in three species of *Delocrinus* furnishes no important new information bearing on classification or interpretation of relationships of this very common Upper Carboniferous and Permian inadunate. The nature of the tegmen is still very inadequately known, but it is noteworthy that discovered features accord wholly with expectations as to probable existence of a sac. Absence of this structure in the case of most specimens of *Delocrinus* and of various other genera merely points to a lesser fitness of the tegminal part of the organism for fossilization. Until proved otherwise, it is reasonable to conclude that all inadunate genera were provided with a more or less distended sac and that in many cases this was a much more delicate part of the test than others. Probably the tegminal plates were not joined together at all in some genera, except by soft tissue that disintegrated on the death of the animal, scattering the ossicles; and a leathery tegminal covering entirely lacking in calcified elements is possible.

DESCRIPTION OF NEW SPECIES

Delocrinus waughi, n. sp.

Plate 1, figures 7a–c

Description of this new species is based on a single nearly complete crown that is undistorted and that shows excellently a distinctive surface ornamentation.

Dorsal cup nearly circular in outline, viewed from below, height about one-third of greatest width, base marked by a deep narrow concavity. The infrabasal circlet is very small, distal parts sloping almost vertically downward, the distal margins 3.3 mm. above the basal plane of the cup. The greatest diameter of this circlet

is barely larger than the diameter of the stem. The basals curve evenly longitudinally, the proximal part sloping strongly downward and forming most of the height of the basal concavity, and the distal part sloping steeply upward to about mid-height of the cup. The mid-length of these plates is plane transversely, so that each plate of this circlet is fully tangent to the basal plane of the cup. The greatest width of the basal plates is a little over two-thirds that of the length. The radials slope steeply upward, with regular curvature except for a flat arcuate area next to the facets, which slope somewhat inward. Length of these plates is about two-thirds of the greatest width. The anal x is an elongate plate that is widest at its mid-length, even with the summit of the radials; the lower part is squarely truncated for contact with the posterior basal, and the upper part slopes steeply inward toward a point between the arms.

The arms are stout and widest at mid-height, where there is a slight bulge of the crown. The first primibrach is a low quadrate segment, with greatest height about one-half the width. The central part of the distal extremity projects somewhat but is not produced in a spine. The first secundibrachs are quadrate segments, but the remainder of each arm is composed of interlocking wedge-shaped plates, as is normal for the genus. The arms are distinctly rounded transversely in the lower part, but flattened in the upper two-fifths; a sharp angulation separates the external face of the arms from the appressed sides.

The entire surface of the dorsal cup and the lower three-fifths of the arms are covered by a strongly marked pattern of large granules and in addition, fairly numerous large rounded tubercles. The height and greatest width of the tubercles is a little more or less than 1 mm. Each radial carries 17 to 24 of the tubercles and each basal about a dozen of them; they are even distributed except that they do not appear on the proximal parts of the basal plates. The nodes along the middle of each arm are larger than those at the sides, and they tend to form a prominent zigzag series. The upper two-fifths of the arms is smooth.

Articular faces of the small round stem carries about 23 short crenellae. The lumen is strongly pentalobate.

Measurements of the holotype in millimeters are as follows: height of crown 43, height of dorsal cup 8, greatest width of cup 22.2, ratio of height to width 0.36, height of basal concavity 5.1, height of proximal tip of basal plate (raB) about basal plane 3.3, height of distal tip of basal plate (raB) above basal plane 3.3, greatest width of basal concavity 12.0, width of stem 2.6, diameter of lumen 0.4, length of basal (raB) 12.5, width of basal 8.7, length of radial 9.4, width of radial 13.3.

Remarks.—This species is distinguished by its ornamentation and the proportions of the dorsal cup. The ornamentation slightly resembles that of *D. nodosarius* Strimple (1939, p. 8) from the Wann formation (Stanton) of northern Oklahoma, but in that species the nodes tend to be elongated in directions normal to the plate margins. *D. granulosus* Moore and Plummer (1940, p. 268) from Des Moines beds of Texas correspond to *D. waughi* in the granulose and tubercled decoration of the plate, but the granules are more delicate and the tubercles somewhat less prominent; also the sutures of the Texas form are somewhat broader and more impressed.

Occurrence.—Hughes Creek shale member of the Foraker limestone, Council Grove group, Wolfcamp series; University of Kansas Loc. 6055 on state highway 4 about 4 miles northeast of Eskridge, Wabaunsee County, Kansas.

Type.—Holytype, Univ. Kansas no. 60551; collected by John Waugh.

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PLATE

EXPLANATION OF PLATE I

Delocrinus granulosus Moore and Plummer, from the Coody sandstone member of the Atoka formation, Sec. 33, T. 15 N., R. 20 E., Oklahoma.

1.—Rubber cast from the external mold, showing distinctive ornamentation of the dorsal cup and arms and the bulging midportion of the arms (xl.5).

2.—Internal mold showing impression of inner side of some of the arms and (above the line of sawed section) the rounded form of the anal sac, terminal spine not shown. Thinness of the plates of the sac is indicated by narrowness of the cavities that outline the sac. These are molds of individual plates. (xl.5).

3.—Drawings showing form of the anal sac (x3). *a*, Cross section of sac at a level above midheight, indicated by position of cut in Fig. 2. The triangular projections are keels along the midline of plates. *b*, Restoration.

Delocrinus sp., Wann formation (Stanton horizon), The Mound, Bartlesville, Okla.

4.—Incomplete crown, from the right posterior side, showing slender anal sac surmounted by vertically directed sharp spine (xl).

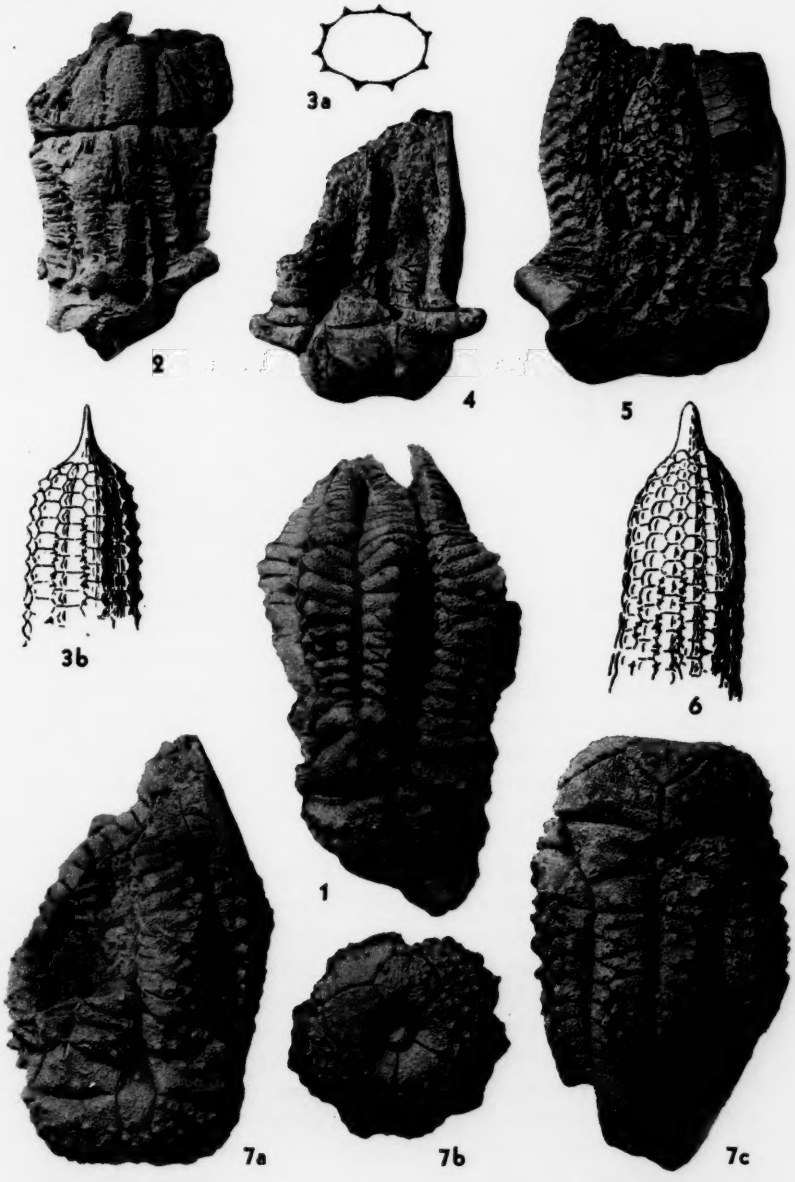
Delocrinus megalobrachius (Beede), Howard limestone, near Topeka, Kans.

5.—Holotype (Univ. Kansas, no. 1832), part of crown removed to show anal sac (xl.2).

6.—Restoration of upper part of anal sac (x3).

Delocrinus waughi, n. sp., Foraker limestone, near Eskridge, Kans. (xl.5).

7.—Holotype (Univ. Kansas, no. 60551). *a*, Posterior view of crown; *b*, Dorsal view; *c*, Anterior view.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FLUORESCENCE AND FLUORESCENT LAMPS

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INTRODUCTION

A light source to be acceptable today must efficiently convert electric energy into light, and for general use this electric energy must be taken from the regular 115–120 volt supply lines. This means that the source must be caused to radiate by the direct or indirect use of electric energy. Two types of radiation process are now used for the production of light. These are incandescence, in which the radiation is a direct result of the temperature of the radiator, and luminescence, in which the radiation is due not to the temperature of the radiator but to some other kind of excitation, such as the passage of electricity through a gas or vapor, chemical action, or irradiation of the source with cathode rays, X-rays, or ultraviolet radiation. This paper will discuss fluorescent lamps in which the luminescence is produced by irradiating certain selected substances, called phosphors, by ultraviolet radiation.

Luminescence is often divided into phosphorescence and fluorescence, the division depending upon the duration of the excited radiation. If the excited radiation continues after the removal of the exciting radiation, it is called phosphorescence, but if the excited radiation is given out only during the irradiation, it is called fluorescence. In this paper, the term fluorescence will be used to denote both fluorescent and phosphorescent luminescence, except where distinction between them is necessary.

Fluorescent substances include both organic and inorganic materials. Some of these materials fluoresce only when in solution, and others only when in the solid state. Fluorescent materials are often used to produce spectacular effects in stage lighting, advertising and display lighting. Another interesting use is

developing for the fluorescent organic materials; that is the lighting of aisles in moving picture theaters. To do this, the rugs in the aisles are dyed with one or more of the organic dyes which, when the rug is illuminated with ultraviolet radiation, fluoresce brilliantly enough that the patron can see his way around. To illuminate these rugs, the radiation from the mercury line at 3650Å is generally used, with the lamp in a glass bulb that will not transmit visible radiation or the shorter ultraviolet radiation. These organic fluorescent materials are not at present used in fluorescent lamps.

Inorganic fluorescent materials in the solid state, such as silicates, borates, and tungstates, are generally used as phosphors for the fluorescent lamps. Certain phenomena of fluorescence are not understood, and exceptions can be found to almost any generalization one attempts to make. Some of the generally observed relations will be pointed out.

RADIATION FROM PHOSPHORS

The character of the radiation given off by the phosphor seems to depend upon the nature of the phosphor and not upon the type of radiation used to produce it. For instance, zinc silicate activated with manganese, will give the same type of fluorescent radiation when it is irradiated with X-rays, with cathode rays, or with ultraviolet radiation in the neighborhood of either the 2537Å line or the 3650Å mercury line. This same thing is also true for some types of sulfides. Calcium fluoride, if heat treated in hydrogen to a high temperature, will give a brilliant blue fluorescent light when irradiated with the 3650Å radiation and some blue radiation when excited with 2537Å radiation. If this same compound is heated in air, it will give a red fluorescence when excited with 2537Å radiation and no response to 3650Å radiation.

ACTIVATION OF PHOSPHORS

Most pure inorganic substances do not fluoresce, but have to be activated by the addition of a small amount of some other material, generally a metallic element. The radiation given off

by the phosphor seems to depend upon the activator and the treatment. Manganese added to many of the fluorescent materials causes them to produce red radiation or green radiation. The method of producing and treating this phosphor determines whether the resulting radiation will be red or green. Silver as an activator tends to produce blue radiation. Cerium, if put into the phosphor in a cerous state, will produce fluorescent radiation in the ultraviolet part of the spectrum. Copper produces green radiation with sulfates.

Some substances that have no added activator do fluoresce, but the methods used in preparing these phosphors leads one to think that they may be activated by the metallic part of the phosphors.

STOKES' LAW

Stokes' law for fluorescence states that the exciting radiation is of shorter wavelength than the excited radiation. This is, in general, true, but there are many seeming violations of this law. Some cases have been reported where nearly a monochromatic radiation has been used as exciting radiation and at least a part of the excited radiation is of shorter wavelengths. This is explained by stating that the excited radiation consists of a band and that the main part of the band is of longer wavelength than the exciting radiation, but the band has been broadened due to some other cause. Another explanation for a seeming violation of Stokes' law is that the molecules of the phosphor possessed some energy at the time of excitation.

QUANTUM EFFICIENCY

Another principle of fluorescence is that one quantum of the exciting radiation will produce but one quantum of the excited radiation. Thus, one quantum of radiation of wavelength 2500Å will produce but one quantum of fluorescent radiation at 5000Å. The application of this principle and Stokes' law always results in an energy loss since the energy of a quantum of radiation varies inversely as its wavelength. Thus 50 per cent of the energy would be lost in the particular case just given.

THEORY OF FLUORESCENCE AND PHOSPHORESCENCE

A plausible explanation of fluorescence and phosphorescence has been developed within the last few years. It can be understood most easily by comparing it with the theory which deals with the emission of light from single atoms and from molecules. The permitted energy levels of a single atom are, in general, widely separated. Consequently, the radiation emitted or absorbed when transitions between these levels are made forms a line spectrum. The permissible energy levels of a molecule consist of groups of closely-spaced levels. In each group, the lower energy levels are the ones most apt to be occupied, but the probability of a higher level being occupied increases with the temperature. The result is that a molecular spectrum consists of bands of closely-spaced lines and that the distribution of intensity within the band varies with the temperature. Transitions from the lowest level of one group to the lowest level of another may be very improbable. In case a transition results in excitation to a relatively high energy level within a group, the molecule then changes to one of the lower levels of excitation in the same group. The difference is converted into thermal energy and is transferred to surrounding molecules. Then the molecule may change to a level of excitation in the group from which the original excitation was made, and may emit radiation of the corresponding wavelength. Again, if this transition results in an unusually high level of excitation within the group of levels, the excess is converted to thermal energy. Thus, the emitted energy usually will be less than the energy of excitation. This means that the spectral maximum of an emission band will be at a greater wavelength than the maximum of the corresponding absorption band.

Excitation and emission processes in a phosphor are similar to these in a molecule. In a phosphor, the interval between energy levels within a group, or band, is less than their intrinsic width. Absorption of radiation within a certain wavelength range excites an electron from the band normally occupied to an upper, unfilled band of energy levels. Because of the close spacing of these levels, both the absorption and the emission

spectra are continuous. Transitions directly back to the original level either are improbable or are ineffective, since the emitted radiation would be absorbed and would excite another electron to the upper band. Emission of radiation from the phosphor is caused by transitions from the upper band to an intermediate level, or from this level to the lower band. However, reabsorption, with eventual conversion into thermal energy, might prevent the successful excitation of fluorescence by the second process. Such intermediate levels, if not an inherent property of the crystal, may be due to defects or foreign atoms in the crystal lattice. The fact that the transition takes place in two or more stages means that the wavelength of the emitted radiation will be greater than that of the exciting radiation. The energy not used in the production of fluorescent radiation presumably is converted into thermal energy.

Mention has been made of the fact that an activator is an essential constituent of most inorganic phosphors of acceptable efficiency. The function of the activator may be the introduction of the intermediate energy levels mentioned above, or the modification of the crystal's energy levels in such a way as to facilitate the excitation process. In some cases, the entire process of excitation and emission may occur in the activator atom.

When there is a metastable level, i.e., one from which downward transitions are very improbable, with an energy a little less than the minimum for the upper band, some electrons will be trapped at this level. If they absorb sufficient thermal energy, they are brought into the upper band and a downward transition with emission of radiation can then occur. This trapping of electrons introduces the delay which is responsible for phosphorescence. This delay may be from a fraction of a second to several hours. Of course, there is some delay, even in fluorescence, between the application of the exciting radiation and the production of the new radiation, but this is only a very small fraction of a second, i.e., of the order of microseconds or even less. This explanation of phosphorescence makes it easy to understand why certain crystals, when irradiated and immediately put in liquid air, will retain a part of their excitation until they have again been

brought to room temperature, even if several hours have elapsed, when they will fluoresce brightly.

DEVELOPMENT OF FLUORESCENT LAMPS

The development of the fluorescent lamp has been very interesting to the engineers in the Nela Park Laboratory because it introduced so many new problems. Among the problems introduced might be mentioned the following: The sources for the exciting radiation had to be decided upon, which meant a study of the various methods of producing short wavelength radiation. The method of operating the low pressure mercury arc also required some study. The best phosphors for the lamps of different colors had to be developed. The method of making the powder adhere to the inside of the tubing had to be worked out. The phosphor on the inside of the tube has to be thick enough to absorb the greater part of the ultraviolet radiation from the low pressure mercury arc, but must not be too thick or it will absorb too much of the light. In either case, if the thickness is not about right, the efficiency of the lamp will be reduced. The size and shape of the tube had to be determined. Is the round tube the best shape for all purposes? Might not an oval or a flat tube be better for some uses?

A great deal of the resources of the Lamp Development Laboratory in both men and equipment have been employed in this development: The physical chemists in developing the phosphors; the electrical engineers and the physists in developing the methods of starting and operating the low pressure mercury arc, including the development of hot cathodes of the proper type; the lamp engineers in making and adapting the various lamp parts to this new lamp. The physicists also assisted in measuring the physical characteristics of the low pressure mercury arc, in studying the sensitivity of the various phosphors and in measuring the spectral distribution and the brightness of the radiation from the finished lamp. The physicists (*1*) also developed the instrument that is used to measure the color of the light output from fluorescent lamps of different types. This instrument is used in the factory as a control device.

SOURCE OF THE EXCITING RADIATION

The first thing to be decided concerning the fluorescent lamp was the source to use to produce the exciting radiation because any advantage either in the efficiency of production of the exciting radiation or in the ease of operation of the arc will be reflected in the characteristics of the fluorescent lamp. This meant a study of the various methods of producing ultraviolet radiation. Many of the various gaseous discharge sources that were known to produce ultraviolet radiation were investigated with the result confirming what had long been known, that is, that a low pressure mercury arc produces resonance radiation of wavelength 2537Å very efficiently.

The early studies that were made of the discharge of electricity through gases showed that the voltage drop at the electrodes, with the electrode materials then used, had a minimum of several hundred volts. At this time, this condition dictated a long tube. Since it was difficult to obtain batteries to give the high voltage necessary to operate the discharge tube, a Ruhmkorff coil ordinarily was used to produce the high voltage. With this coil there was no advantage of a tube with a large diameter since the current was necessarily low. On the other hand, since there was such a large voltage drop at the electrodes, a voltage of several thousand had to be used to obtain a light source of satisfactory efficiency.

The terms *anode* and *cathode*, used to distinguish the electrodes in a gaseous discharge lamp, were originally applied by Faraday to the end regions in a liquid electrolytic cell. The analogy is an interesting and illuminating one, but must not be allowed to conceal the real differences between the two phenomena.

In metallic conduction, the transfer of charge is almost purely electronic, although there is some dispute as to whether the presence or the absence of electrons contributes more to the passage of current! In liquid electrolytes, the negative and positive ions both contribute materially to the passage of current. In water, the most mobile ion is the (positive) hydrogen ion; in liquid ammonia, the most mobile is negative, an electron loaded with one or more molecules of ammonia.

In gaseous conduction, charge is carried by the uncombined negative electron, whose mobility is of the order of one thousand times that of a positive mercury ion, this case being thus intermediate between those of metallic and of electrolytic conduction.

Just as there are polarization effects at the electrodes of a liquid cell, and concentration changes which are not observed in a uniform column, so in a gaseous discharge the phenomena at the anode and particularly at the cathode differ from those in the comparatively uniform "positive column". The adjective, "positive", here refers not to electric charge but to the particular spectrum of nitrogen shown in this part of the discharge in air (or nitrogen); there is only a very slight excess positive volume charge, due to the greater mobility of the electron. The special electrode effects still contribute 15 or 20 volts to the discharge potential in mercury, the contribution of the positive column to the discharge potential varying with the length and vapor pressure, and inversely with the tube diameter.

THE LOW PRESSURE MERCURY ARC

Resonance radiation of wavelength 2537Å is produced more efficiently in the positive column than in the "negative glow" at the cathode or in the anode glow. To attain a reasonable efficiency, the greater part of the voltage must be spent in the positive column. Thus the fluorescent lamp is necessarily long in relation to its diameter. For lamps operated at the usual lighting-circuit voltages, the electrode losses reduce the possible efficiency some 10 to 20 percent. This percent loss may be reduced by increasing the temperature or lowering the "work function" of the cathode, i.e., making it easier for the electrons to escape, or by designing lamps to be operated, e.g., with a step-up transformer, at higher voltage. The cathode fall of potential is not entirely wasted, since there is a luminous region, the "negative glow" near the surface of the cathode. Negative-glow lamps containing neon are used when it is desired to produce a little light, as for night lights or "tell-tales", at the ordinary lighting-circuit voltages and when efficiency is a secondary consideration.

EFFICIENCY OF THE LOW PRESSURE MERCURY ARC

Maximum efficiency of production of resonance radiation in a low pressure mercury arc is attained only when the coolest portion of the tube wall has a certain temperature. This is to be expected because the pressure of the mercury vapor in the tube depends on the temperature of the walls. If this pressure were too low, the concentration of mercury atoms available for excitation would be insufficient for maximum efficiency; if it were too high, i.e., the wall temperature too high, most of the resonance radiation would be absorbed before it reached the tube wall and much of it would be lost. The spectral distribution of the radiation from mercury vapor varies with the pressure, a smaller proportion being resonance radiation as the pressure is increased. The curves (*2*) in Figures 1, 2 and 3 show how the production of the resonance radiation depends (1) upon the length of the tube (for a given diameter), (2) upon the temperature of the walls of the tube and (3) upon the current density for a definite tube diameter. Data (*3*) on the production of the radiation by a low pressure mercury arc for different temperatures are given in Table 1. These data show that as much as 60 percent of the input energy will be radiated in the line at 2537Å for an 18-inch by 1-inch tube with the walls at a temperature of 48°C and for very low current density (low temperature of tube walls), a much higher percentage of the input will be radiated in this line. (See Figure 2.) No other known source of radiation can transform such a high percentage of the electrical energy input directly into so narrow a band of radiation as is done by this low pressure mercury arc. Transforming electrical energy into visible radiation by using a tungsten filament is much less efficient. The 500-watt, 120-volt tungsten-filament lamp when operating at the temperature (2940°K) to give a life of one-thousand hours, radiates only about 12 percent of the input energy within the visible spectrum, which extends from about 4000Å to 7600Å, while the low pressure mercury arc radiates as much as 60 to 70 percent of the input energy within the line at 2537Å which is less than one Angstrom wide!

It was found, as was expected, that the very large voltage

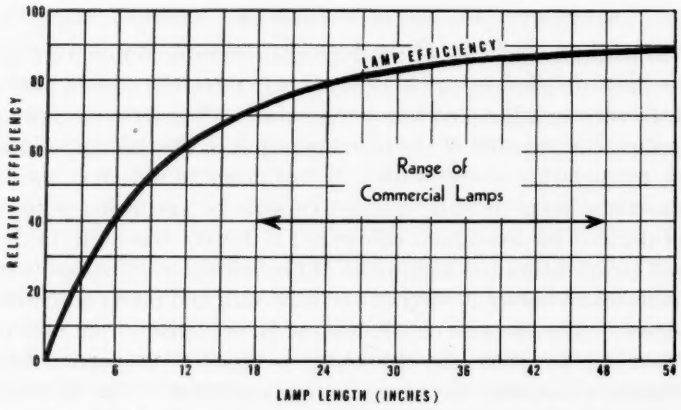

FIG. 1.—Relative lamp efficiency vs. length of tube for fluorescent lamps

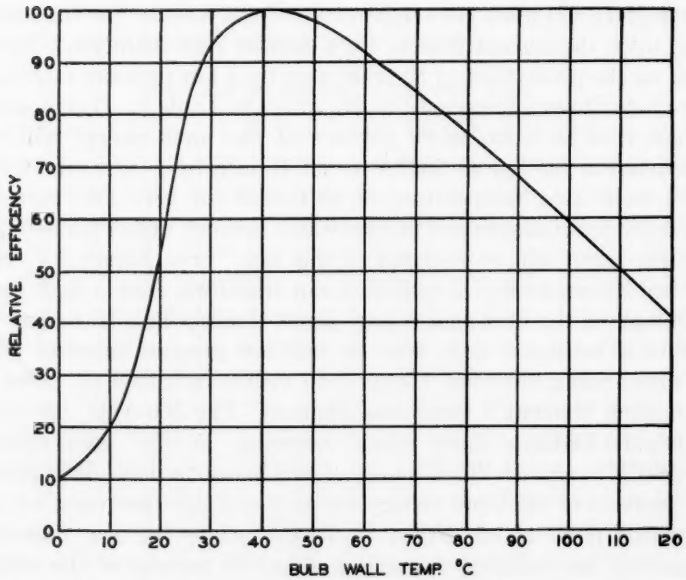

FIG. 2.—Percentage of total input energy converted into mercury resonance radiation ($\lambda = 2537\text{Å}$) for different temperatures of tube wall for a discharge tube 1 inch in diameter.

drop at the cold cathodes could be greatly reduced by the use of selected hot cathodes which, of course, increases both the efficiency

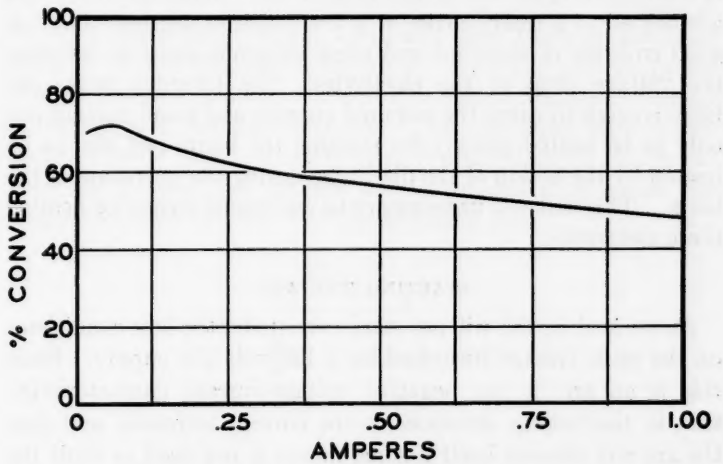

FIG. 3.—Percent of total input energy converted into mercury resonance radiation (λ = 2537Å) for different currents for a discharge tube 1 inch in diameter held at 40°C.

TABLE 1

Efficiency of production of mercury line radiation

CURRENT (AMP.)	BULB WALL TEMP.	PER CENT* CONVERTED INTO EACH LINE							SUM	PROPORTION IN 2537A* LINE	LUMENS PER WATT*
		λ2537	3129	3654	4047	4358	5461	5708A			
	°C.									*per cent*	
0.25	48	62	0.53	0.45	0.59	1.30	0.86	0.18	65.9	94	5.5
.50	57	55	.68	.62	.86	1.45	1.26	.27	60.1	92	7.3
1.00	69	40	.89	.82	1.02	1.79	1.49	.39	46.4	86	10.0

* Of positive column input, for a low pressure discharge tube of 1-inch diameter in still air at 25°C.

of production of the resonance radiation and the ease of operating the resulting lamp. These hot cathodes are similar to the ones used in some radio tubes. In this case, they are made of small

coils of tungsten wire coated with electron-emitting materials such as barium and strontium carbonates which, during the process of manufacture, are converted to the oxides. When such cathodes are heated to a temperature of a few hundred degrees, they are good emitters of electrons and these electrons assist in lowering the voltage drop at the electrodes. The tungsten wires are large enough to carry the required current and small enough not only to be heated quickly for starting the lamp, but also to be heated by the action of the discharge during the operation of the lamp. This makes it unnecessary to use special means for heating these electrodes.

STARTING THE ARC

An arc such as this will not start, even under the best conditions, on the peak voltage furnished by a 120 volt a.c. supply. Since this is an arc, it has negative voltage-current characteristics, that is, the voltage decreases as the current increases, and thus the arc will destroy itself if some means is not used to limit the current. In this case, the current is limited by the use of a choke coil selected to keep the current at the value desired. Advantage is taken of this choke coil to make a starting device. The circuit used to start and operate the lamp is shown in Figure 4. When the current is first turned on, the switch "S" is closed and thus the current flows through the two electrodes in series and heats them to the desired temperature. The switch "S" is so made that after a very short time, but long enough to allow the cathodes to become heated, it opens, then the peak of the voltage kick due to the stopping of the current through this choke coil is enough to start the lamp.

There are at least three types of switches used to open the circuit and thus start the lamp. The first was a magnetic switch operated by the magnetic field of the choke coil; the second, a thermal switch which was operated by the passage of the current through a heater coil located near a bimetallic part of the switch and finally a combination thermal switch and discharge tube (*4*).

The bimetallic part of this last switch is enclosed in a small discharge tube so made and containing gas at such a pressure that it will start to glow on the regular 115 or 120 volts. As soon as the tube starts to glow, the bimetallic part heats up and thus closes the circuit and stops the glow. Now the current passes through the electrodes and the switch cools off again, breaking the circuit and starting the lamp. This discharge tube switch has to be made very accurately since it must start on 115 to 120 volts, but it must not operate on the voltage drop across the lamp which may be 30 to 50 volts less than this.

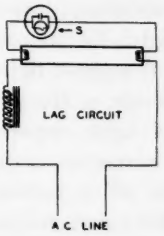

FIG. 4.—Operating circuit for fluorescent lamps

RESULTS OF USING THE LOW PRESSURE MERCURY ARC

The use of the low pressure mercury arc as the source of the exciting radiation for the fluorescent lamps makes certain conditions necessary. First, the lamp must be in the form of a tube that is long with respect to its diameter and the current density must be low. Second, since resonance radiation from this arc is very harmful to the observers' eyes, it must not be allowed to escape into the room. This dictates that the arc be in a glass tube that does not transmit this short wavelength radiation. This is not difficult because most glasses have practically no transmission for wavelength 2537Å. Again, if the radiation cannot pass through the walls of the bulb used, the fluorescent powder must be on the inside of the tube. Putting the phosphors on the inside of the tube gives certain other advantages: The powder will not get dirty, nor is it apt to get rubbed off and thus, it will give a longer service. The idea of coating the phosphor on the inside of the tube was suggested by W. S. Andrews (*5*),

who was working on mercury arcs in the General Electric Research Laboratory at Schenectady and used this method for increasing the light output of the arcs some thirty years ago. It is interesting to note that Edison (*6*) experimented with fluorescent powders on the inside walls of X-ray tubes some 45 years ago. He produced "fluorescent lamps of several candlepower" but was obliged to drop the work due to harmful effects of the X-ray.

DEVELOPING OF THE PROPER PHOSPHORS

The next problem was investigation of the phosphors. Many natural compounds fluoresce when ultraviolet radiation falls upon them. Among these might be mentioned willemite, a zinc orthosilicate which gives off a green light when ultraviolet radiation falls upon it; zinc blende, a zinc sulfide which gives green, yellow or blue fluorescent light, depending upon the impurity present as the activator; wernerite, a sodium-calcium-aluminum chloride-silicate that gives off a yellow light when ultraviolet radiation falls upon it; the ruby, which is an aluminum oxide and gives off a red fluorescent radiation; fluorite, a calcium fluoride which fluoresces with a blue light. In addition to the above, many other silicates and some of the sulfides, borates and tungstates were known to fluoresce when ultraviolet radiation fell upon them.

Starting with this information, the chemists and the engineers set out to develop phosphors suitable for fluorescent lamps of various colors. It was known that the pure inorganic substances did not, in general, fluoresce, but that there had to be some foreign material present as an activator; however, the effects of the kind and amount of the various impurities, i.e., activators, on the resulting fluorescence, were not well known. It was found that it was not sufficient to have the activating material present as a physical mixture, but that it had to be in the form of a solid solution. Some of the activators produced results that depended upon the character of the material used to introduce the activator into the compound; others, upon the treatment of the activated compound. Cerium is an activator for calcium phosphate, but not all cerium compounds can be used to introduce the activator.

The color of the fluorescent light from zinc silicate, activated with manganese, depends upon how rapidly the compound is cooled after being heated to a high temperature. A very slow cooling gives a green fluorescent material, a more rapid cooling gives a yellow fluorescent compound, and a very rapid cooling gives a red fluorescent material.

Since the low pressure mercury arc is used as the source of the exciting radiation, it is advantageous to develop phosphors with maximum sensitivity to radiation of wavelength 2537Å.

It was found that the heat treatment and the methods used to reduce the phosphor to a powder affected the fluorescent efficiency of the compound. Certain materials were found to reduce fluorescence (*7*) seriously, they had to be eliminated from the compound. Notwithstanding these difficulties, the chemists were able to produce a satisfactory line of phosphors for the purpose, and were able to improve on the radiating characteristics of the natural fluorescent compounds. One example of this improvement will be pointed out (*2*). When the engineers first started to work on this problem, they obtained some natural willemite from Franklin, N. J., ground it to a powder, and used the resulting powder to make a fluorescent lamp. This lamp had an efficiency of about 30 lumens per watt, although made from natural materials. A tungsten-filament incandescent lamp (a 40-watt, 120-volt lamp) of the same light output as this lamp, which was a 15-watt lamp, has an efficiency of about 12 lumens per watt. That is, using only natural materials, a fluorescent lamp was made that had an efficiency of over 2.5 times that of the tungsten-filament incandescent lamp of the same light output. Of course, one must remember that the fluorescent light was green, and not of the same color as that from the tungsten lamp. Later, synthetic zinc orthosilicate, activated with manganese, was made in the Laboratory. When this was used as a phosphor, the resultant fluorescent lamp had an efficiency, in the 15-watt size, of about 65 lumens per watt. This increase in efficiency was brought about by purifying the initial materials, using the proper amount of activating materials and the best methods known for heat treating and for reducing the material to powder. Like, or even greater, increases in efficiency were brought about

in some of the other new synthetic compounds as compared to the natural fluorescent compounds. As a result of an immense amount of work, phosphors have been made that make it possible to produce the line of lamps listed in Table 3. This work on the study of compounds and the treatment of phosphors is being continued, since the present-day phosphors do not meet all the demands for fluorescent lamps of various colors. To mention one of these demands, there is a need for a better red-producing phosphor than is at present available.

TESTING THE PHOSPHOR

The wavelength sensitivities of the phosphors were tested by measuring the light output when they were exposed to a measured

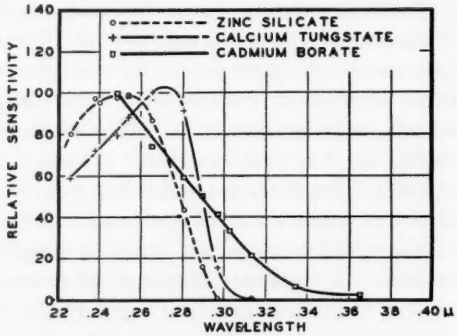

FIG. 5.—Relative spectral excitation sensitivity of various phosphors

amount of radiation of various wavelengths from about 2200Å to 4000Å. It was found that some of the silicates, borates, and tungstates could be so activated that their maximum sensitivity came at or near the 2537Å line. On the other hand, most of the sulfides were found to have their maximum sensitivity at or near 3650Å. The sensitivities of the phosphors that are used in present day fluorescent lamps are given in Figures 5 and 6.

Fluorescent materials when excited give off, in general, wide bands of radiation. Some materials, such as benzene vapor and uranyl salts at low temperature, give narrow bands of fluorescent radiation. The radiating characteristics of the materials used as phosphors in the fluorescent lamps has been investigated by

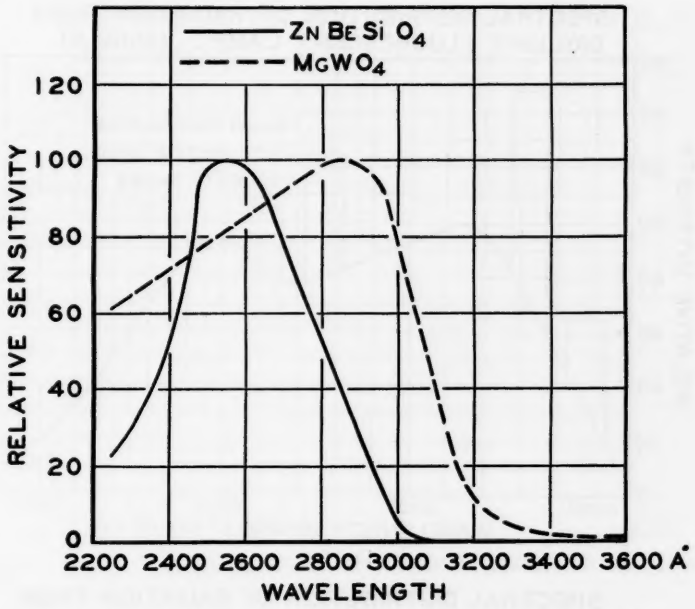

FIG. 6.—Relative spectral excitation sensitivity of various phosphors

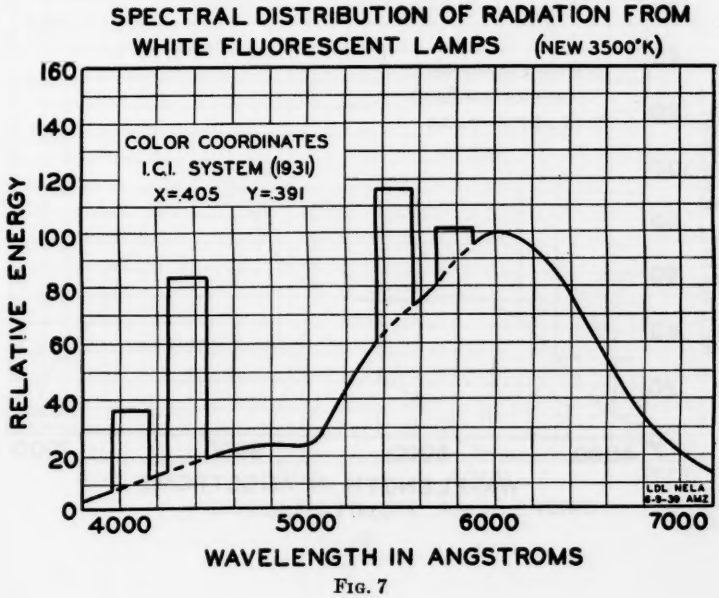

FIG. 7

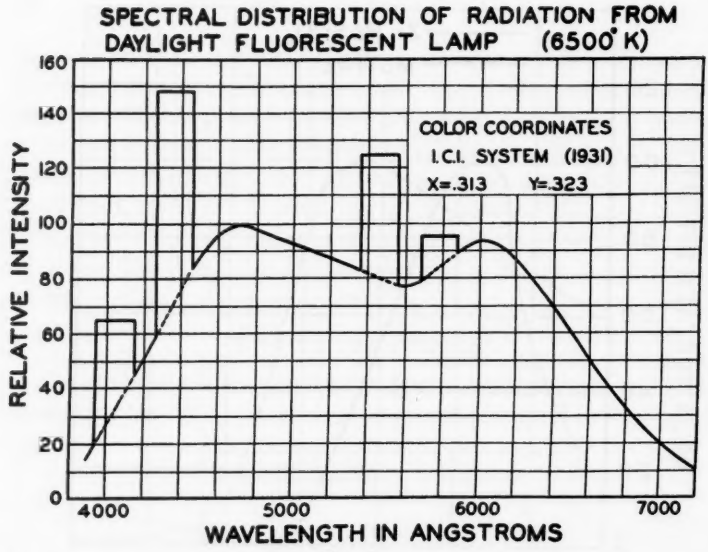
SPECTRAL DISTRIBUTION OF RADIATION FROM
DAYLIGHT FLUORESCENT LAMP (6500° K)
COLOR COORDINATES
I.C.I. SYSTEM (1931)
X=.313 Y=.323
RELATIVE INTENSITY
0
20
40
60
80
100
120
140
160
4000
5000
6000
7000
WAVELENGTH IN ANGSTROMS

FIG. 8

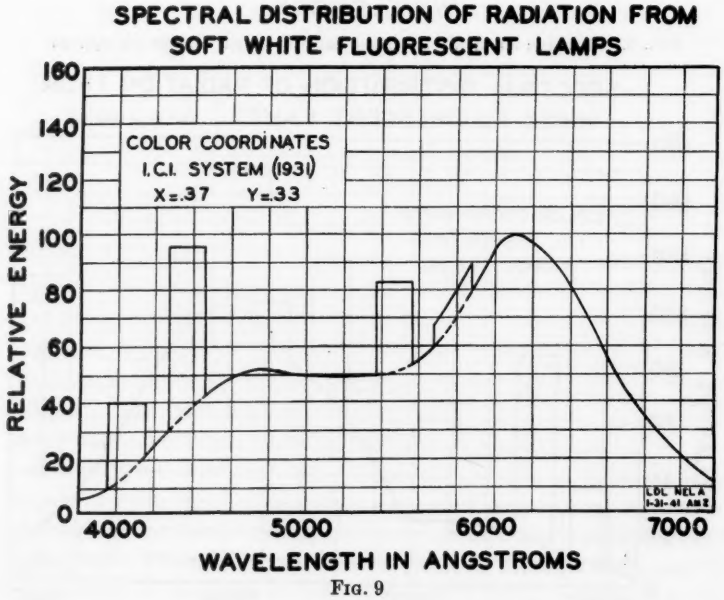
SPECTRAL DISTRIBUTION OF RADIATION FROM
SOFT WHITE FLUORESCENT LAMPS
COLOR COORDINATES
I.C.I. SYSTEM (1931)
X=.37 Y=.33
RELATIVE ENERGY
0
20
40
60
80
100
120
140
160
4000
5000
6000
7000
WAVELENGTH IN ANGSTROMS

FIG. 9

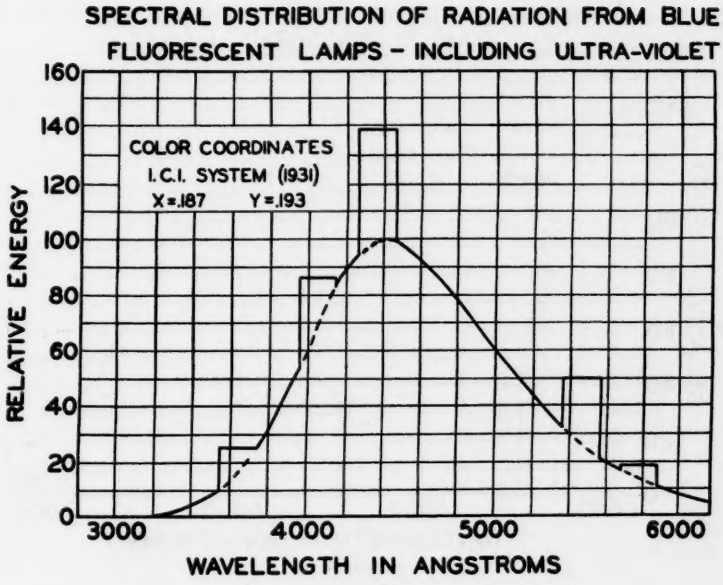
SPECTRAL DISTRIBUTION OF RADIATION FROM BLUE FLUORESCENT LAMPS – INCLUDING ULTRA-VIOLET
COLOR COORDINATES
I.C.I. SYSTEM (1931)
X=.187 Y=.193
RELATIVE ENERGY
160
140
120
100
80
60
40
20
0
3000
4000
5000
6000
WAVELENGTH IN ANGSTROMS

FIG. 10

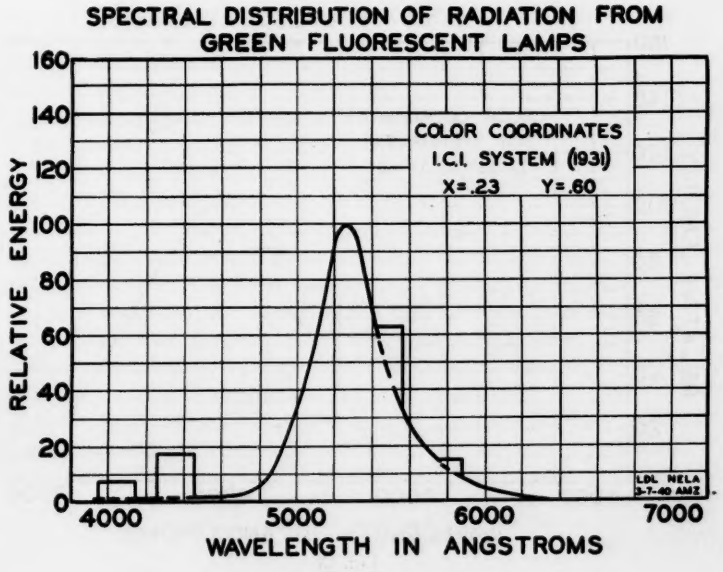
SPECTRAL DISTRIBUTION OF RADIATION FROM GREEN FLUORESCENT LAMPS
COLOR COORDINATES
I.C.I. SYSTEM (1931)
X=.23 Y=.60
RELATIVE ENERGY
160
140
120
100
80
60
40
20
0
4000
5000
6000
7000
WAVELENGTH IN ANGSTROMS

FIG. 11

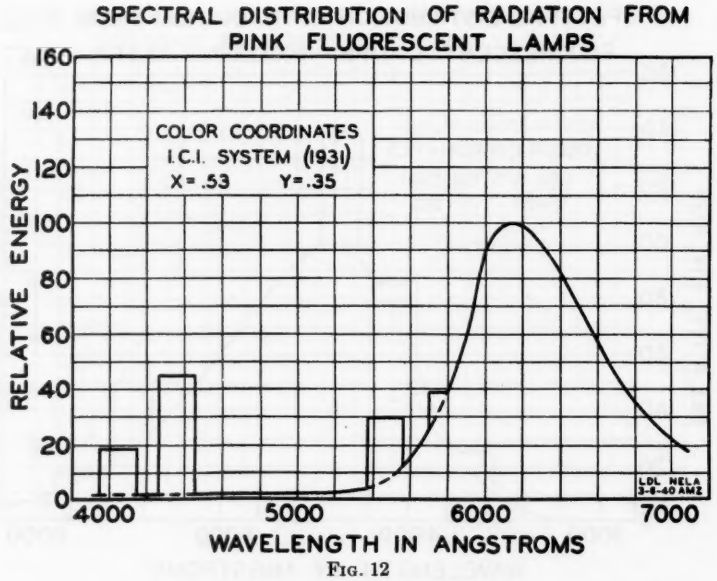
SPECTRAL DISTRIBUTION OF RADIATION FROM
PINK FLUORESCENT LAMPS
COLOR COORDINATES
I.C.I. SYSTEM (1931)
X=.53 Y=.35
RELATIVE ENERGY
160
140
120
100
80
60
40
20
0
4000
5000
6000
7000
WAVELENGTH IN ANGSTROMS
LDL NELA
3-6-40 AMZ

FIG. 12

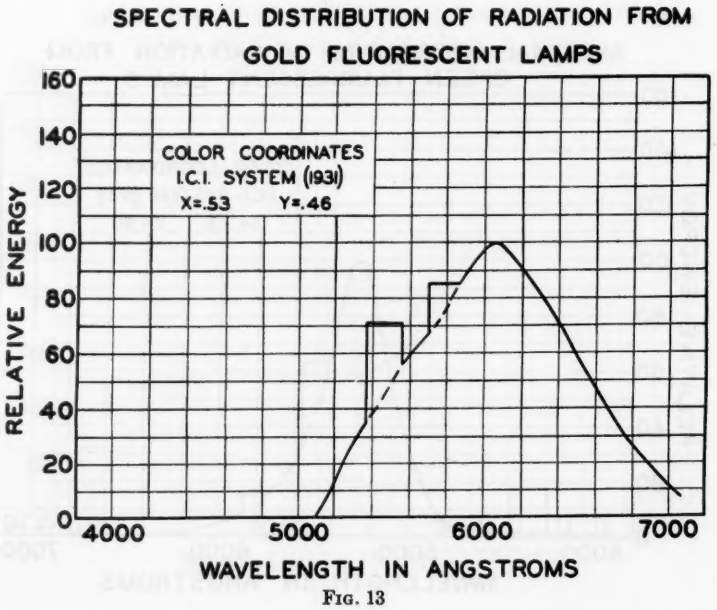
SPECTRAL DISTRIBUTION OF RADIATION FROM
GOLD FLUORESCENT LAMPS
COLOR COORDINATES
I.C.I. SYSTEM (1931)
X=.53 Y=.46
RELATIVE ENERGY
160
140
120
100
80
60
40
20
0
4000
5000
6000
7000
WAVELENGTH IN ANGSTROMS

FIG. 13

measuring the relative spectral intensity of the light emitted from standard fluorescent lamps. These results are shown in Figures 7 to 14. These last two investigations were made possible by the use of our large double monochromator (*8*) with quartz optical parts.

OPERATION OF FLUORESCENT LAMPS

Fluorescent lamps are, in general, operated on 60-cycle a.c. with a choke coil in the circuit to regulate the current. The

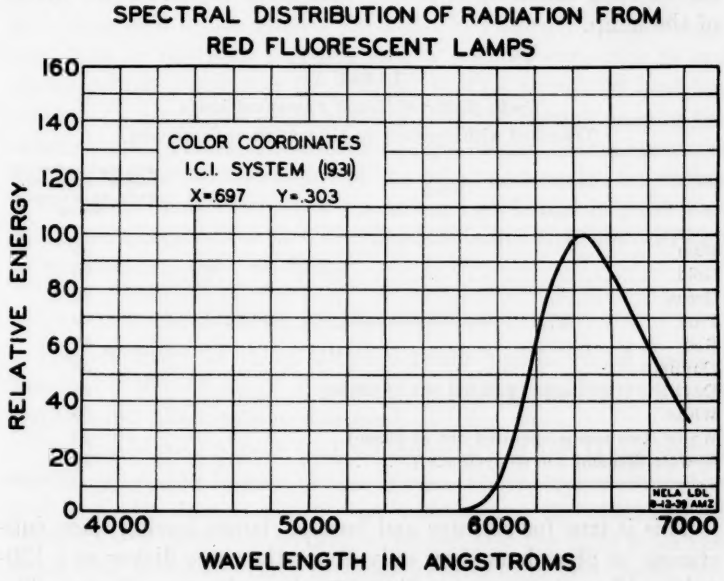

FIG. 14

use of a choke coil causes the current to lag behind the voltage. This results in a low power factor. The low power factor can be brought back to a value of about 90 percent by the use of a selected capacitor across the line. One type of fluorescent lamp, the RF, operates on rectified a.c. The rectifying equipment takes the place of the choke used with other types.

FLICKER OF FLUORESCENT LAMPS

Another disadvantage results from the operation of these lamps on alternating current. The radiation from a low pressure

mercury arc follows very closely the variation in the current through the tube. Since this current passes through zero 120 times per second, the radiation from the low pressure mercury arc falls to zero with the same frequency. This results in flicker whenever moving objects are observed. Fortunately, most of the phosphors used in the fluorescent lamps have enough phosphorescent radiation, that is, the excited radiation decays slowly enough, that they furnish some radiation during the period when the exciting radiation is zero. This helps to reduce the flicker of the lamp.

TABLE 2

Cyclic flicker of 15-watt fluorescent lamps

(Operated with reactors on 115-volt 60-cycle circuits)

COLOR	PER CENT DEVIATION (PLUS AND MINUS) FROM MEAN CANDLE-POWER
Blue	95
Gold	20
Green	20
Pink	20
Red	10
Daylight	55
Daylight (two lamps operated out of phase)	25
White	35
White (two lamps operated out of phase)	16
40-watt filament (on 60 cycle a.c.)	16

This is true for silicates and borates; lamps having these substances as phosphors show only about the same flicker as a 120-volt, 15-watt tungsten-filament incandescent lamp. The tungstates, however, show almost no phosphorescence. Lamps in which tungstates are used as phosphors, i.e., blue fluorescent lamps, show marked flicker.

The light given by the low pressure mercury arc furnishes from 5 to 10 percent of the light output of the various fluorescent lamps. Since it falls to zero 120 times per second and is blue-green in color, fluorescent lamps will, in general, show a color flicker in addition to the intensity flicker. The data in Table 2 show the percentage flicker of the various fluorescent lamps.

METHODS OF REDUCING FLICKER

There are two methods of operating fluorescent lamps that help to reduce flicker. If a number of fluorescent lamps are used together and three phase a.c. is available, flicker can be greatly reduced by operating a part of these lamps on each of three different phases. With this method of operation, the points of minimum light output of the lamps do not all come at the same time. Since they are out of step by 120°, the flicker has three times the usual period, (that is, a flicker of 360 per second), and there is a much smaller variation in intensity. The lamps may also be operated in pairs with a selected capacitor in one circuit which will cause the current in this circuit to lead the voltage by about the same amount that the current lags in the other circuit. Thus, the maximum light output of one lamp will overlap the minimum output of the other and again, the flicker is reduced. This method of operating two lamps in pairs also results in a high power factor. The RF lamps that are operated on rectified a.c. show no flicker.

EFFICIENCY OF FLUORESCENT LAMPS

The efficiency of these lamps depends upon several factors. The first is the efficiency of production of the exciting radiation and this has already been discussed.

One would also expect that the efficiency of the lamps would depend upon the length of the tube. The variation with the length of the tube is due to the variation in the efficiency of production of both the exciting radiation and the light from the fluorescent powder. Both of these have certain end losses, but by far, the greater loss in efficiency is due to the reduction in the efficiency of producing mercury radiation caused by the end losses. This is due to the voltage loss at the cathodes which is more or less constant and does not depend upon the length of the tube.

The bulb wall temperature, current density and lamp size had to be compromised in order to keep the size of the lamp down. The efficiency of production of light might be increased several percent by varying these relations to suit certain conditions for the maximum production of exciting radiation. The final result

aimed at was the production of the best lamp possible. The efficiency of the final lamp also depends upon the character of the phosphors used and upon the success that is attained in having powder of the proper thickness (*9*), which will absorb practically all of the exciting radiation and still let through a large percentage of the light that is produced on the inner side of the phosphors.

FLUORESCENT LAMPS AND AIR CONDITIONING

Fluorescent lamps are more efficient than lamps of some other types, that is, there is less energy expended for a given amount

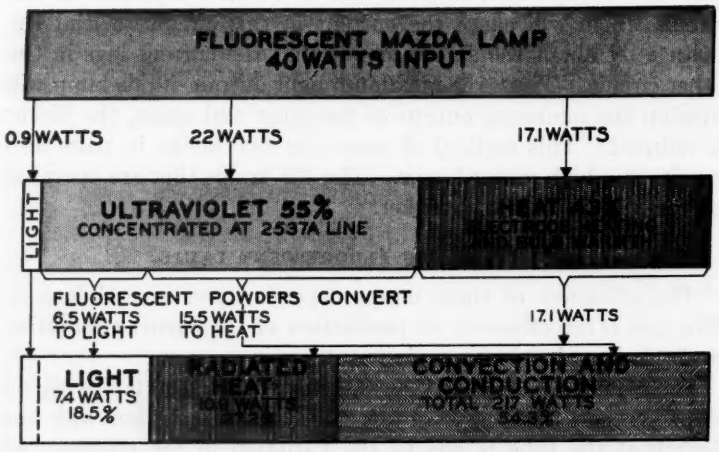

FIG. 15.—Dissipation of energy from a 40-watt fluorescent lamp

of light with this type of lamp than for some other lamps. In addition to this, a smaller percentage of the input energy is radiated than for a tungsten-filament incandescent lamp (Figure 15). Comparisons between this lamp and other sources should be made on the basis of equal light output, thus, a 40-watt fluorescent lamp operating at 50 to 52 lumens per watt (total lumens about 2100) should be compared with a 120-volt, 100 to 150-watt gas-filled tungsten-filament lamp (total lumen output about 1600 to 2600). These gas-filled tungsten lamps have certain losses (*10*) in converting the input energy to radiation with the

result that only about 84 percent of the input, for the 150-watt lamp, that is, 126 watts, is radiated by the filament and the bulb. About 9.6 percent of this is within the visible spectrum, less than 0.1 percent in the ultraviolet, about 39 percent in the near infrared (7600 to 14000Å) and about 35 percent in the very long infrared. The other 24 watts is conducted and convected away by the air. The 40-watt white fluorescent lamp radiates only about 45.7 per cent of the input, or about 18.2 watts, and most of this is radiated by the bulb and thus is of very long wavelength. The other 21.8 watts is conducted and convected away by the surrounding air. About this same relation between light and energy radiated holds for comparisons between larger fluorescent lamps and larger tungsten lamps. This shows that, for the same amount of light, the fluorescent lamp radiates only about one-fourth as much energy as the tungsten lamp. These comparison data apply to lamps operated in the open. If a shade or enclosing jacket is used with either lamp, a somewhat larger percentage of the energy from each lamp will be carried away by the surrounding air. The fluorescent lamp has a great advantage for use in rooms that are to be air conditioned since in the first place there is much less energy let loose in the room and only about one-fourth as much energy for the same amount of light is radiated into the room. Most of the energy that is carried away from the lamp by the conduction and convection of the air will remain in the upper part of the room where the lamps are located and can be removed by ventilation.

"COLD LIGHT"

The fluorescent lamp may thus be spoken of as more nearly a cold light than the tungsten lamp. Cold light is an expression that does not mean what it says. This expression usually refers to a source that uses all of its energy within the visible spectrum for the purpose of producing light. Such a lamp would not be cold, but would be colder, for the same amount of light, than a lamp such as the tungsten lamp that uses a major part of its energy to produce radiation in the infrared part of the spectrum.

TABLE 3

Characteristics of Mazda F lamps

	9″ T-5	15″ T-12	18″ T-8	24″ T-12	36″ T-8	48″ T-12	60″ T-17	58″ T-9½* RF
Nominal Lamp Watts†	6	14	15	20	30	40	100	85
Approx. Lamp Amps.	0.15	0.37	0.30	0.35	0.34	0.41	1.45	
Approx. Lamp Volts	45	41	56	62	103	108	72	
Circuit Voltages	110–125	105–125‡	110–125	110–125	199–216 220–250 110–125	199–216 220–250 110–125	199–216 220–250 110–125	
Diameter	⅝″	1½″	1″	1½″	1″	1½″	2⅛″	1 3/16″
Rated Avg. Life, Hrs.§	750	1500	2500	2500	2500	2500	2000	3000

Lumen outputs¶ and brightnesses‖

	LUMENS	c/cm²	LUMENS	c/cm²	LUMENS	c/cm²	LUMENS	c/cm²	LUMENS	c/cm²	LUMENS	c/cm²	LUMENS	c/cm²	LUMENS	c/cm²
White	180	.84	460	.44	615	.74	900	.56	1450	.85	2100	.60	4200	.75	4000**	.68
Daylight	155	.72	370	.36	495	.60	730	.46	1200	.70	1700	.48	3350	.60	4000††	.68
Soft white	...	...	...	...	435	.53	640	.41	1050	.62	1500	.43	....	...	....	...
Blue	...	...	...	...	315	.38	460	.29	780	.46	....	...	....	...	....	...
Green	...	...	...	...	900	1.10	1300	.82	2250	1.33	....	...	....	...	....	...
Pink	...	...	...	...	300	.36	440	.27	750	.44	....	...	....	...	....	...
Gold	...	...	...	...	375	.56	540	.34	930	.55	....	...	....	...	....	...
Red	...	...	...	...	45	.05	60	.04	120	.07	....	...	....	...	....	...

* The type RF lamp is a special type of fluorescent lamp used on rectified current from specially designed auxiliary equipment.

† Add auxiliary watts for total.

‡ Voltage range for two-in-series operation in which a specially designed filament lamp (60 volts, ½ ampere, S-11 outside-white bulb, intermediate-screw base is used as a resistance ballast. Total wattage of two lamps is 45 on a.c., 38 on d.c.

§ Under specified test conditions.

¶ Lumen output ratings apply at the end of 100 hours of operation.

‖ Maximum values at center of lamp perpendicular to the lamp. Brightnesses are sometimes given in foot-lamberts. 1 candle/cm² = 2919 foot-lamberts.

** Blue white.

†† Industrial white.

ADVANTAGES OF FLUORESCENT LAMPS

Fluorescent lamps have many advantages over some of the other sources of light. In the first place, the light is produced at a much higher efficiency by fluorescent lamps than it is by tungsten-filament incandescent lamps. Some data on the characteristics of fluorescent lamps are given in Table 3. With fluorescent lamps it is easy to produce light of almost any color one desires. While the increase in efficiency may be two or three times that of the tungsten lamps for the fluorescent lamps that one would use for general lighting, the fluorescent lamp is many times more efficient in the production of colored light. If a tungsten lamp is used to produce colored light, it must be done by the use of filters, that is, the subtractive method must be used. This means that some of the light must be thrown away. The efficiency of producing colored light by the subtractive method depends upon the efficiency of the lamp used as the basis and also upon the characteristics of the filter used. The comparative results given below are those obtained when about the same amount of light is produced in each case and when the best glass filter known for the purpose is used. If the comparison were made between the fluorescent lamp and the tungsten-filament lumiline lamp, the results would be still more favorable to the fluorescent lamp. Green light can be produced directly by fluorescent lamps at an efficiency of 70 lumens per watt, while similar green light would be produced by use of a tungsten lamp and a glass filter at about 2.5 lumens per watt. To produce a daylight lamp by the use of a tungsten lamp and the subtractive method, a blue glass must be used. The transmission of the blue glass depends upon how nearly the daylight is to be matched. The glass used on the ordinary daylight bulb transmits about 50 to 60 percent of the light and gives a color temperature of about 5000°K. The best glass we have ever found for this purpose, if used with a 120-volt, 500-watt tungsten-filament lamp, will produce a good match for daylight at 6500°K and will transmit about 17.3 percent of the light from the lamp—thus producing daylight at an efficiency of about 3.5 lumens per watt. A good daylight fluorescent lamp can be made with an efficiency of 35 to 45 lumens

per watt. Not only is this much more efficient than the blue tungsten lamp, but it furnishes a better substitute for daylight. All the colored lamps listed in Table 3 are produced without use of filters except the dark red and the gold. To produce these two colors, it was found necessary to eliminate, with a filter, some of the blue mercury radiation. These filters are in the lamps on the surfaces of the glass tubing. Red light is produced at an efficiency of 3 lumens per watt by means of a fluorescent lamp with an integral filter. Red light of the same character can be produced by a tungsten lamp and a separate red filter at an efficiency of about 1.5 lumens per watt.

EFFECT OF VARIATION OF VOLTAGE

The light output of fluorescent lamps is not affected by voltage variation to the same extent as is that of tungsten lamps. The power delivered to the lamp is influenced by the kind of operating equipment and by the characteristics of the choke used in this equipment. In general, with the type of auxilliary ordinarily used, a 1 percent change in the applied voltage causes a 2 percent change in the light output of the fluorescent lamps. This same change in the voltage applied to an incandescent lamp produces about a 3.5 percent variation in the light output. Curves showing the variations of lamp voltages, lamp current, lumen output and overall efficiency with changes in line voltage are given in Figure 16. These results were obtained by using a 15 watt, 18-inch by 1-inch lamp and a standard auxilliary consisting of a large, high-quality choke with a magnetic switch. It is interesting to note that the lamp voltage goes down as the line voltage is increased and that, although the lumen output increases, the efficiency decreases.

LIFE OF FLUORESCENT LAMPS

The life of the fluorescent lamp is influenced by several factors. Some of these factors are inherent in the lamp and some are the results of the method of operating it. The electrodes of fluorescent lamps must furnish the electrons necessary to start and to maintain the current through the mercury vapor without being

heated unduly; otherwise, their life will be short. This depends in part upon the size of the electrodes and in part upon the character and treatment of the material coated on them. If the electrodes are too large, they may not be heated by the bombardment to a high enough temperature to maintain the arc in its proper condition; if they are too small, they may be heated to too high a temperature and thus have a short life. The lamps have to be exhausted very carefully, otherwise, the danger of

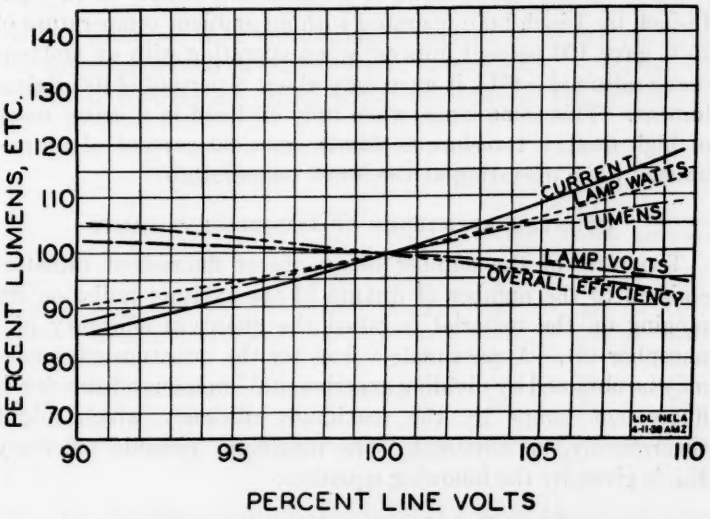

FIG. 16.—Characteristic curves for typical fluorescent lamp

blackening is increased. In general, fluorescent lamps lose their usefulness due to the decrease in their light output before they fail to operate. This depreciation of their light output results from blackening of the fluorescent coating, due to two causes. The first is the effect of the mercury on the coating and the second is the effect of the materials vaporized from the electrodes. The latter is the major cause of the blackening near the ends of the lamp that occurs late in the life of the lamp.

Fluorescent lamps are designed to give their best performance

within a definite temperature range. The curve in Figure 2 shows how the light output of these lamps changes with a variation in the bulb wall temperature. This change in light output is almost entirely due to the change in the output of the exciting radiation from the low pressure mercury arc as the bulb temperature is changed. The light given by the phosphors shows only a slight change with temperature if the exciting radiation is kept constant. Here is one example of the effect of temperature changes on the light output of a fluorescent lamp. A 15-watt, 18-inch by 1-inch bulb operated with an ambient temperature of 25°C gave 100 percent lumens; when operating with an ambient temperature of −9°C, it gave only about 8 percent of its original lumens. This same lamp, when fully enclosed in a jacket made of high quality translucent plastic, gave 80 percent of normal lumens while operating at the lower temperature.

QUANTUM EFFICIENCY OF FLUORESCENT LAMPS

The ratio of the number of quanta of fluorescent radiation emitted to the number of quanta of the exciting radiation impinging on the material is called the quantum efficiency of a phosphor (3). Approximate values for the quantum efficiencies may be obtained by dividing experimental luminous efficiencies[1] of fluorescent lamps by the maximum efficiency which might, theoretically, be obtained. The maximum possible efficiency, E_M, is given by the following equation:

$$E_M = 621 \cdot C \cdot R \cdot 0.45 \cdot 0.90 = 251 \cdot C \cdot R \text{ lumens per watt.}$$

C is the luminosity coefficient of the fluorescent radiation, defined by the equation $C = \int_0^\infty J_\lambda K_\lambda d\lambda / \int_0^\infty J_\lambda d\lambda$. $J_\lambda d\lambda$ is the intensity of the fluorescent radiation of wavelengths between λ and $\lambda + d\lambda$ and K_λ is the relative luminosity. Then, $621 \cdot C$ is the ratio of lumens radiated to watts radiated. R is the quantum ratio, defined as the mean ratio of the energy per quantum of fluores-

[1] The luminous efficiencies discussed in this paragraph are those for the fluorescent radiation alone; i.e., lamp efficiencies minus the efficiency (4 lumens per watt) produced by the mercury line radiation.

cent radiation to the energy per quantum for the 2537Å line. The quantity 0.45 is the fraction of the input wattage, to a lamp 1-inch in diameter and 18-inches long, which is converted into 2537Å. The quantity 0.90 is the estimated fraction of the fluorescent radiation which gets out of the lamp.

Experimental luminous efficiencies are quoted for the individual lamps which gave highest values, because they best indicate inherent phosphor efficiencies. The results are shown in Table 4. These values are not inherent in the use of the compounds listed; on the contrary, they are markedly dependent on the purity of the constituents and on the method of preparation. Although the process of preparation differs widely for different phosphors, and

TABLE 4

Quantum efficiency of phosphors

PHOSPHOR	LUMINOSITY COEFFICIENT	QUANTUM RATIO	CALCULATED* LUMENS PER WATT	BEST MEASURED* LUMENS PER WATT	QUANTUM EFFICIENCY
$CaWO_4$	0.21	0.58	30	21	0.70
$MgWO_4$	.37	.53	50	35	.70
$ZnSiO_3$	.78	.48	95	70	.74
$(Zn,Be)SiO_3$	.55	.43	60	32	.53
$CdSiO_3$	.53	.42	55	30	.55
CdB_2O_5	.34	.41	35	23	.66

* Excluding mercury line radiation, which adds four lumens per watt to efficiency.

each has required a long development, all these phosphors have reached quantum efficiencies between 0.53 and 0.74, and four of the six lie between 0.66 and 0.74. Since quantum efficiencies of phosphors improve with a decrease in the intensity of impinging radiation and with reduction in temperature (*11*), the values 0.66–0.74 may be near a limit for the conditions under which the lamps are operated.

COLOR OF FLUORESCENT LAMPS

The colors of fluorescent lamps have been classified by use of the system of color specification adopted in 1931 by the International Commission on Illumination. In this system,

a color is identified by the proportions of three standard colors, called primaries, in a mixture which matches the color. The

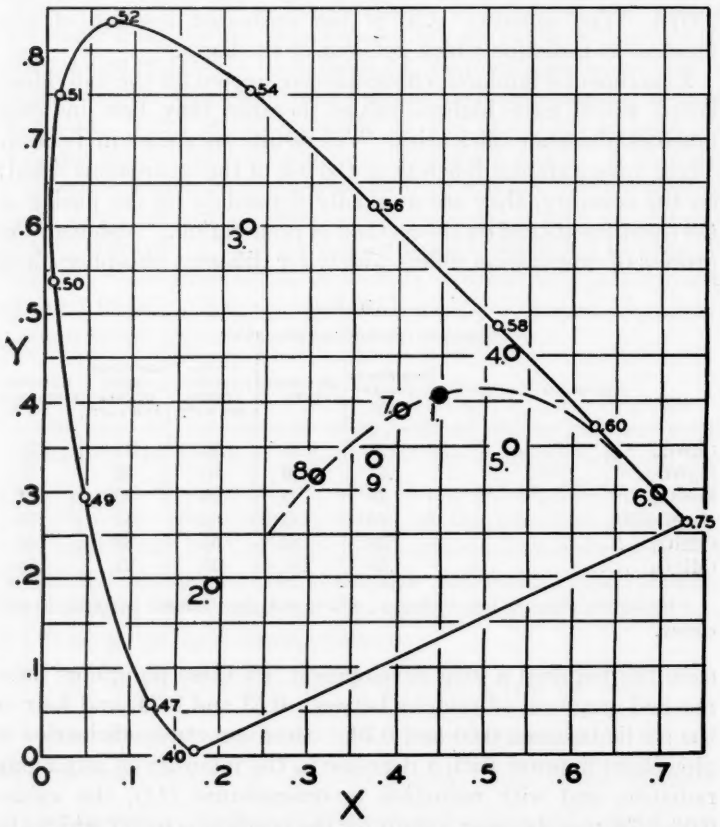

FIG. 17—I.C.I. color diagram showing color of various fluorescent lamps and some other source for comparison. The spectral colors are marked on the outside curve; the dashed curve shows the blackbody colors. 1, tungsten lamp, color temperature 2848°K; fluorescent lamps, 2, blue; 3, green; 4, gold; 5, pink; 6, red; 7, white; 8, daylight; and 9, soft white.

primaries, X, Y and Z, of this system have certain characteristics, not found among real colors; yet they are defined in terms of

colors which are reproducible in any laboratory. The rating of a color in terms of these primaries may be done by computation, using spectral intensity data, or by measurement, using an instrument called a colorimeter. In either case, color[2] can be specified by color coordinates x, y and z, which are the proportions furnished by the primaries X, Y and Z respectively in the mixture which matches the color. Since $x+y+z \equiv 1$, any two of them determine the third and, therefore, suffice to define the color.

Color ratings often are plotted on an x, y diagram, such as Figure 17. The solid curved line on this diagram is the locus of color points for the pure colors of the spectrum. The points for light of certain wavelengths, designated in microns on the graph, are indicated by circles.

All real colors are represented by points in the area on Figure 17, bounded by the spectrum locus and the straight line which connects the ends of this locus.

Points representing the colors of blackbodies at various temperatures fall on the dashed line of Figure 17. The points for tungsten filament lamps lie on, or very close to, this curve. The point labelled 1 in this figure is that for tungsten at a temperature of 2848°K.

The color points for standard Mazda fluorescent lamps of various colors are indicated by numbered circles on Figure 17. The position of these points indicates that the color of the red lamp is almost identical to that of a pure spectrum color. The color of the gold lamp is a fairly saturated one; that is, it approaches that of a spectrum color. The colors of the green, blue and pink lamps are much less saturated than that of the gold one. The 3500° white, the soft white and the daylight lamps all have colors within the range commonly called white.

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DAKOTASUCHUS KINGI, A CROCODILE FROM THE DAKOTA OF KANSAS

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Elsewhere the writer has called attention to crocodile remains from the Dakota sandstone of Kansas.[1] In the following pages is given a detailed description of the specimen briefly characterized in this earlier report.

OCCURRENCE AND HISTORY OF THE FIND

The specimen on which the following description is based came to my attention some years ago through the kindness of Dr. A. W. Giles, professor of geology at the University of Arkansas. In 1931 he recalled that some years earlier, when connected with Kansas Wesleyan University, he had noticed the specimen there in an unorganized collection. No record was made of the specimen and much of its history as recalled by the authorities of Kansas Wesleyan is vague.

Mr. A. Wheeler Jones, at the time connected with Kansas Wesleyan University, presented the specimen to the school, probably in the first decade of the century. He was a trained geologist and if the record is correctly remembered it may be depended upon as given by him. The remains, in a large concretion weathered from the Dakota sandstone, are said to have come from near Salina, Kansas, but the exact locality of the occurrence has not been determined. The appearance of the concretion is much like that of a vast number that are strewn over the Dakota outcrop to the west of Salina. It would not be surprising if some of these, or the many concretions that have been utilized for buildings or ornamental construction in the towns and country homes of this region, are found to encase other important vertebrate records.

[1] Mehl, M. G.: Crocodilian Remains from the Dakota Sandstone of Western Kansas (Abstract). Geol. Soc. Am., Proc. for 1933, p. 368, 1934.

NATURE OF THE MATERIAL

Originally the specimen was an elongate iron cemented sandstone concretion that inclosed a skeleton that may well have been complete. The typical finely mammillate surface of an outer zone of highly concentrated iron cement characteristic of such concretions seems to have outlined closely the shape of the skeleton. The portion preserved consists of two closely fitting sections totalling approximately four and a half feet in length with a fresh break at either end. The break at the anterior end lost the skull and a few of the immediately following cervical vertebrae. The posterior break comes just back of the sacrum. The outer surface of much of the remaining part of the concretion has been lost either in normal weathering or by exploratory chipping and with it has disappeared most of the bone of the ventral and dorsal armor. There is evidence that at least the right front leg was preserved in part, in a mass projecting from the concretion proper. None of this was preserved at the time of this study except the proximal end of the humerus. The perfect impression of the armor, and the pelvic and pectoral girdles, along with some of the bony material, give an adequate idea of the nature of these parts. Apparently most of the ribs and vertebrae are well preserved in the interior of the concretion.

Details of the skeleton such as could be determined from these remains without further injury to the specimen follow.

THE DORSAL SHIELD

One of the most striking features is a flexo-rigid dorsal shield or carapace that completely covers the dorsal and dorso-lateral region from mid-length of the neck to the base of the tail, made up of twenty pairs of plates. This shield is sharply arched transversely and broadly arched longitudinally. Measured along the convex surface it is about 124 cm. long and 43 cm. wide.

Each plate that goes to make up the carapace is cleanly outlined in the matrix. In addition several of the plates are preserved in their entirety and others are preserved in part. In much probability small dermal scutes were distributed along the dorsal side of the tail but these plates, if present, formed no part of the cara-

pace proper. The shape and size of the last plate preserved at each end indicate that it is the last of the overlapping series.

The right and left member of each pair is rigidly united at the median line, in some cases by irregular suture. The carapace as a whole has been preserved with little distortion except that two pairs of plates overlying the shoulder girdle were forced up at their distal ends as the shield was pressed down on the ends of the scapulae. Each paired unit, except the last, appreciably overlaps the following unit throughout much of its length. In addition most of the units have a conspicuous anteriorly directed process on the lower anterior-lateral edge which underlies the anterior-adjacent plate to direct its glide when the carapace as a whole is laterally flexed.

The plates correspond with vertebral spines in position, each overlap coming directly above a spine terminus. The posterior margin of the first (anterior) plate lies above the first of the dorsal vertebrae. The spine of the last cervical centers beneath the anterior half of the first plate pair. Although there is this correspondence between vertebrae spines and dorsal plates there is no evidence that spines and plates were fused. On the contrary, there is evidence that the spines failed to reach the plates by an appreciable distance.

In transverse sections at their mid-length all the plates are more or less lens-shaped with moderately sharp edges. They probably average 1.3 cm. thick in longitudinal section at mid-width. The first two pairs are gently curved, concave downward, throughout their length and seem to be fairly uniform in thickness, except that they thin rapidly at the distal ends to moderately sharp edges. The following plates are nearly all straight in their proximal half or two-thirds with a moderately sharp downward curvature of the distal ends. The majority of the mid-length and posterior plates seem to maintain their full thickness or show an actual increase toward their broadly rounded distal ends.

The under side of all the plates is smooth except that the first and second pair are beveled or slightly offset upward at their posterior edge for an overlap on the following plate. The dorsal surfaces of the relatively few plates preserved have been abraded

and have lost any minor features of ornamentation that may have been present. A small piece of matrix that covered part of the proximal end of the twelfth plate of the left side indicates that the plate surface was marked by irregularly arranged small rounded pits of about 0.3 cm. diameter.

The outline of all the plates is more or less rectangular with lengths from two to nearly three times the width. The axis in each is slightly curved, concave forward. The width does not vary greatly except that the first and the last few are appreciably narrower. The length increases from each end of the series to the maximum which is nearly constant from the fifth to the eleventh inclusive. Measurements of the plates are shown in the following table.

Dorsal plate measurements

PLATE NUMBER	WIDTH	LENGTH	PLATE NUMBER	WIDTH	LENGTH
	cm.	*cm.*		*cm.*	*cm.*
1	6.4	14.0	11	7.7	21.1
2	6.5	15.8	12	7.1	21.0
3	6.4	17.3	13	6.9	19.9
4	6.6	19.5	14	7.2	17.7
5	6.8	21.6	15	7.3	16.5
6	7.1	21.4	16	7.3	15.6
7	7.1	21.2	17	6.5	14.3
8	7.3	21.7	18	6.0	13.5
9	7.6	21.4	19	4.7	11.7
10	7.7	21.9	20	3.3	9.8

THE VENTRAL ARMOR

A more or less rigid armor almost completely covered the ventral side. It extended over the ventro-lateral areas to the ends of the dorsal plates, from near the anterior end of the pubes to within a short distance of the pectoral girdle. This armor is composed of heavy, closely fitting polygonal plates, most of them hexagonal in outline, arranged with close approximation to bilateral symmetry, the two sections joining along a nearly straight median line. Nearly all of the plates are missing but short, low separating ridges on the matrix clearly mark the position of nearly every plate.

Each lateral half of the greater part of this shield is made up of four antero-posteriorly directed rows of plates. Each row, designated by number from the median line outward, consists of six plates of major size, the individuals of which are staggered with those of laterally adjacent rows. A fifth row of four plates of major size forms the posterior two-thirds of the lateral margin. The anterior third of the lateral margin is formed by the anterior two plates of the fourth row. At the posterior and anterior margins is a larger number of smaller, less regularly arranged plates and isolated ossicles. The maximum width of the shield, at about a third its length from the posterior end, is 52.2 cm. The maximum length, along the median line, is about 47 cm. The posterior width is greater than that of the anterior end. Antero-posteriorly the shield seems to have been nearly flat. The transverse section, now obviously flattened, seems to have been broadly rounded with more sharply upcurved margins.

The individual units of the first row of major plates are all more or less pentagonal in outline with nearly straight anterior and posterior borders. The straight inner margins are the longest and join similar edges of directly opposed plates of the opposite side of the median line. The outer margin is formed by two straight lines that form an angle of approximately 120°. The angle fits into the angles between the hexagonal plates of the second row which alternate in position with those of the first. The first (anterior) plate of row one is about 6.3 cm. long and 6.1 cm. wide. Back of this there is a fairly regular diminution in size to the posterior plates of the series which is about 5.2 cm. long and 4.5 cm. wide. The plates of the second and third row are subequal, about 6.8 cm. long (antero-posteriorly) and 7.6 cm. wide. All are more or less regularly hexagonal in outline. The first and the last plate in each of these rows is somewhat smaller than the others and departs somewhat from the hexagonal symmetry.

The fourth row of major plates is much like the third in size and proportions except that the outer edge of the two anterior plates seem to have been rounded instead of angular, to form part of the more or less regular margin of the shield. The posterior plate of this series seems to have been truncated posteriorly.

The fifth or lateral margin row probably consisted of not more than four plates, all more or less pentagonal in outline and smaller than the other major plates.

All evidence indicates that the plates of the major group were thick, probably 1 cm. or more. The impression of the under side of each is nearly flat and smooth except, in some cases, for faint striations without regular orientation, crossed like the impression of coarsely woven cloth. The outer surface of the few major plates preserved is broadly convex with rough surface suggesting radial ornamentation. That the major group of plates was closely united is evidenced by their lack of displacement in contrast with the minor plates at the anterior and posterior ends. Furthermore, the shield as a whole, nearly flat as preserved, except at the margin, still preserves parts of strong lateral curvature involving more than individual plates, a pattern such as results from the irregular flattening of a curved sheet of metal.

At the anterior edge of the shield are preserved a dozen or more small bone plates and the impressions of many more. The larger of these, some reaching a diameter of 3.5 cm., fit close together and form a continuation of the anterior median part of the shield. They are irregular in shape, but approach square outlines. In front of these are still smaller plates, more or less circular and ranging down to less than 1 cm. in diameter, forming an irregular fringe. Many of these are more or less isolated. The area about the posterior margin of the shield is not well preserved, but the impression of a few small sub-circular plates indicates a margin similar to that of the anterior end.

THE VERTEBRAE COLUMN

There is evidence of 21 consecutive vertebrae within the concretion that encases the skeleton, a series starting near the middle of the neck and including the base of the tail. With few exceptions the termini of the vertebral spines are exposed because of the general loss of the dorsal plates which would otherwise conceal them. Some information concerning the vertebrae is gained from the exposure of the ribs along the sides of the concretion and from a few cross sections of diapophyses. More exact information

is to be had from sections through natural molds of three vertebrae.

CERVICAL VERTEBRAE AND RIBS

The position and some of the details of four cervical vertebrae and their associated ribs are evident through the partial exposure of cavities left by the loss of most of the bone. These vertebrae are the posterior four; numbers 5, 6, 7, and 8. There is some uncertainty in this identification due to the fact that the last of these and the first of the immediately following vertebrae cannot be satisfactorily studied without preparation of the specimen that would injure other important parts of the record. There is, of course, no assurance that eight is the characteristic number of cervicals for this group.

Vertebra number five of this series is preserved as the mold of its posterior side. Details of other parts cannot be determined. The posterior face of the centrum is nearly circular, with a diameter of about 5.2 cm. It is regularly and moderately concave with a central depth of about 0.7 cm. The total height of the vertebra is 13.2 cm. The diameter of the core of the neural canal is 2 cm., a measurement back of midlength of the canal that may be somewhat greater than its most restricted part. The neural spine is thin and not conspicuously expanded at its terminus. It is about 2.3 cm. high, 0.4 cm. thick, and 2.1 cm. wide at the upper end. The spread of the post-zygopophyses is approximately 5.6 cm.

The sixth cervical is evident through a small opening into the lower anterior end of its natural mold which is still partly filled by bony structure, the tip of the spine, and the molds of its ribs. The anterior face of the centrum is apparently of the same proportions and dimensions as the posterior face of the fifth. The parapophyses arise from below mid-height of the centrum and have a spread of about 6.6 cm. The diapophysial spread can be but little more than this and possibly may be somewhat less. The ventral side of the centrum is marked by a strong round-edged keel which, at the anterior end, extends as a conspicuous process below the anterior face. The ribs are much like those of the same region in modern crocodilians. The capitular process is excep-

tionally stout and is conspicuously expanded both vertically and antero-posteriorly. It extends outward horizontally from the parapophysis. The tubercular process is apparently longer than the capitular process and is comparatively thin and slender without conspicuous expansion at its terminus. Both processes join the rib shaft at an angle of somewhat less than 90° with its anterior extension. The centers of the capitular and tubercular facets are separated by a space of about 2.1 cm. The posterior part of the rib shaft is of small diameter and is tapered to a sharp point. The length, measured from the center of the articular surface, is 4.3 cm. It is directed backward and slightly out and down.

The seventh cervical vertebra is entirely encased by the matrix except the tip of the spine and the mold of the left rib which is exposed along its outer edge. This rib, except in its measurements, is not markedly different from the seventh. It is 10 cm. long along the outer edge of the shaft which is nearly straight, and gradually tapered to a sharp point, both anteriorly and posteriorly, from its greatest diameter, about 1 cm. This greatest diameter is at the base of the capitular and tubercular processes, about a third the length of the shaft from its anterior end. The capitular and tubercular processes are of about the same thickness as those of the preceding rib and are of somewhat less antero-posterior diameter. These processes curve inward from the shaft and are directed forward and less inward. Their length cannot be determined but they do not appear to reach as far forward as the sharp anterior end of the shaft. The length of the shaft in front of its union with the processes is 2 cm. The rib is directed horizontally back and slightly outward.

The last cervical vertebra, if properly identified, is evident through the tip of the spine and a very little of the anterior end of the left rib. The spine, like the three preceding, is narrow and thin, without terminal expansion. It differs from the spines that immediately follow it in that they are much more massive and are terminally expanded. The present position of the spine of the eighth cervical is beneath the center of the anterior half of the union of the first pair of dorsal plates. There is no evidence that it has been displaced from its normal position.

The rib seems to be very much like that of the seventh except for the suggestion that it is somewhat more slender and the anterior projection of the shaft is somewhat less. The posterior end of the seventh rib overlaps the anterior end of the eighth for a distance of 1.8 cm.

THE DORSAL VERTEBRAE AND RIBS

Thirteen vertebrae are assigned to the dorsal series. Of these the spines of six are exposed along the median dorsal line of the specimen, two more are represented by cross sections through their transverse processes, and one is represented by a complete natural mold such that it has been possible to reproduce it in plaster. Of the dorsal vertebrae that are thus accounted for each corresponds in position with the posterior edge of a pair of dorsal plates. The first spine is at the posterior edge of the first plate pair and the last, which is also the last of the dorsal series, is at the posterior edge of pair thirteen.

There are two spaces where no vertebrae are exposed, between plate pairs six and nine and between pairs ten and eleven. It is assumed that these spaces are occupied by three vertebrae and one vertebra respectively with relations to the dorsal plates as are shown in the other vertebrae. As further evidence of the number of dorsals, there are 11 pairs of stout, typical thoracic ribs present that correspond well with the position of the 11 anterior dorsal vertebrae and there is evidence of two more pairs of short slender ribs at the posterior end of the series.

The only clue to variations among the vertebrae from one end of the series to the other is in the spine development. There is an abrupt change from a thin, unexpanded spine of the last cervical to a conspicuous lateral expansion of the terminus of the first dorsal.

The second spine of this series reaches the maximum lateral terminal expansion, about 1.6 cm., which is maintained by several of the vertebrae that follow. Starting with about the seventh vertebrae the spines increase in width and decrease in thickness and terminal expansion toward the dimensions of the last of the series.

The thirteenth and last dorsal vertebra, reproduced in plaster with a fair degree of accuracy from the natural mold, is not of perfect bilateral symmetry and the measurements recorded are averages. The centrum is stout with maximum length, along its dorsal side, of 6.2 cm. The length along the ventral side is 5.6 cm. In lateral view the faces are set off, flange-like, from the barrel which is further reduced by regular construction to a mid-length diameter of 4 cm. (Figure 1.)

The anterior face is subcircular in outline with vertical and transverse diameters of 5.4 cm. and 5.8 cm. respectively. This face is regularly concave to a central depth of 1 cm. The posterior face, less nearly circular in outline than the anterior face, has greatest vertical and lateral diameters of 5.8 cm. and 5.2 cm.

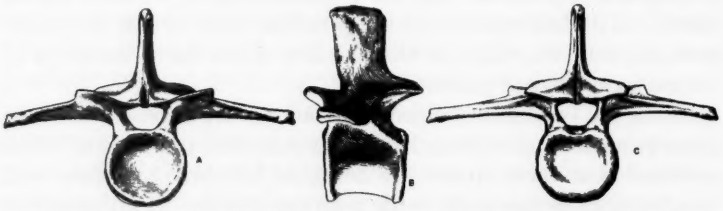


FIG. 1.—*Dakotasuchus kingi* Mehl. A-C—anterior, left lateral, and posterior views respectively of the last dorsal vertebra, ¼ natural size.

respectively. The central part of the upper edge is excavated so that the median vertical diameter is only 4.8 cm. This face is moderately concave with the greatest depth, about 0.3 cm., above its center. The total height of the vertebra is 14.2 cm. The neural canal is more or less heart-shaped, particularly at its posterior end, with average lateral and median vertical diameters of 3 cm. and 2 cm. respectively.

The transverse processes project laterally from high on the arch and are slightly down curved. At mid-length they are about 3.2 cm. wide. They are 1 cm. thick at the posterior edge with the anterior edge thin and moderately sharp. A conspicuous buttress arises from the posterior base of the arch to strengthen the transverse process. The ends of these processes are slightly thickened, expanded anteriorly, and divided into fairly distinct

capitular and tubercular facets. The spread of the processes is 21.5 cm.

Both the posterior and anterior zygopophyses are really extensions of the edges of the transverse process with the articular surfaces nearly on the level of its upper surface. The spread of the pre-zygopophyses is 10 cm. Their large, nearly flat articular faces are directed up and very slightly inward. The spread of the post-zygopophyses is 7.5 cm. and their flat articular facets are directed downward. The greatest antero-posterior extent of the pre- and post-zygopophyses is about 8.7 cm.

The neural spine is about 5.2 cm. high and at mid-length is 0.9 cm. thick and 3.6 cm. wide. Its terminus is slightly expanded antero-posteriorly and laterally. The arch is deeply notched between the pre- and the post-zygopophyses, particularly the latter, with the posterior notch extending half the length of the neural spine as a shallowing groove on its posterior edge.

THE DORSAL RIBS

Details of the dorsal rib series cannot be determined although much of the shaft and distal ends of 11 pairs of stout ribs are exposed along the edges of the hard matrix. All seem exceptionally long and sharply curved toward the proximal end. The distal ends of the series from the sixth to the eleventh are somewhat expanded. The section of the twelfth and the thirteenth at the middle of the shaft is small and circular. The lengths cannot be determined. At the end of the transverse process of the thirteenth dorsal vertebra is a mold, apparently of the proximal end of a rib. This mold indicates the presence of distinct tubercular and capitular facets. It seems likely that this is the impression of the thirteenth dorsal rib, almost in normal position, because of the distinct facets indicated on the vertebral process as described above. There is no indication of uncinate processes on the ribs but there is the possibility that the preservation is such as to fail in recording them.

THE LUMBAR VERTEBRAE

Between the last of the free rib bearing vertebrae and the true sacrals are three vertebrae the first two of which are to be classed

as lumbars. The third, in reality a modified lumbar, functions as a sacral and is so described.

The only evidence of the lumbars is the exposure of the distal end of the transverse process of each on the left side of the concretion. These termini are thin and both are about 2.5 cm. wide.

THE SACRAL VERTEBRAE

The pelvis articulates with three vertebrae, a modified lumbar and two true sacrals. The right and left transverse process termini of the first of these, the modified lumbar, are exposed. They are about 3.5 cm. wide and 1 cm. thick. Instead of extending horizontally as the diopophyses of the normal lumbars they are bent back and down so as to closely approach the first true sacral. In cross section they are slightly crescentic, concave down and forward. Their articulation near the anterior end of the ilium, is the smallest of the three but cannot be questioned.

Both of the true sacrals have the tip of the spine and the right and left rib termini exposed. The spine of the first is 3.8 cm. wide and about 1.2 cm. thick. That of the second is of the same thickness, but is somewhat narrower. The articulations of the first with the ilium are about 5.0 cm. long and 3.4 cm. wide, oval in outline with long axis parallel and almost directly above the axis of the ischium, as viewed laterally. The ischiatic articulations of the last sacral are about 7.0 cm. long and average about 2.0 cm. wide with somewhat greater thickness at the lower end. The long axis of this articulation is very slightly curved concave up. The upper end is tilted back so that its axis forms an angle of about 45° with that of the ischium.

CAUDAL VERTEBRAE

The caudal series is represented by a single vertebra, a cross section near the anterior face of the first. The outline of the anterior face of this vertebra is sub-circular, about 6.0 cm. wide and 5.0 cm. high, with lower margin flattened. The neural spine is thin and comparatively short. The total vertebral height is about 10 cm. The anterior zygopophysial spread is 5.0 cm. The spread of the transverse processes is probably about 11.0 cm. Other details are lacking.

THE VENTRAL RIBS

The ventral rib system, always complex in the crocodiles, is represented in the present specimen by abdominal ribs only. In much probability, this is the fault of preservation as much as it is the lack of ossification. The region between the ventral shield and the clavicles is deeply abraded so that there is no chance for the preservation of anterior thoracic ventrals. Possibly some of the ventral system is concealed beneath the shield although this fails to conceal some of the abdominal rib series.

ABDOMINAL RIBS

One of the most striking features of the abdominal rib system is a pair of bars that constitute what may be designated as the pubic guard. These rods, with more or less circular section at midlength of about 1.6 cm. diameter, are tapered posteriorly to vertically spatulate termini about 1.6 cm. wide. The posterior halves of the ribs are nearly straight. The anterior halves curve inward and seem to have been united at the median line, about 7.5 cm. in front of the anterior edge of the pubes. The straight posterior halves parallel and lie close to the outer edge of the pubes and extend fully two-thirds the length of this margin.

In the space between the anterior end of the pubes and the pubic guard is one pair (possibly more) of short rods just behind the guard and paralleling it. These short rods, about 6.5 cm. long, closely approach each other or are actually fused at the median line. At their anterior end they are circular in section with a diameter of about .8 cm. They taper to pointed posterior extremities.

In front of the guard are preserved, either as impressions or as actual bone, four pairs of rods that converge toward the median line. All seem to be circular in cross section with maximum diameters of about 0.9 cm.

THE PECTORAL GIRDLE

The nature of the pectoral girdle is recorded in an adequate natural mold of the scapula and the coracoid of the right side, and by part of the interclavicle. From the natural molds it has

been possible to make nearly perfect plaster casts of the scapula and the coracoid. (Figure 2.)

THE SCAPULA

The scapula of this form departs from normal crocodilian development most noticeably in that it is more thickened at the proximal end, the shaft is somewhat more twisted, and the distal end is much more expanded than is common. The length of the scapula paralleling the posterior edge is 15.8 cm. The diagona

FIG. 2.—*Dakotasuchus kingi* Mehl. A–C—lateral views of right scapula, right coracoid, and direct posterior view of right scapula and coracoid respectively, ½ natural size.

measurement from the upper posterior corner to the lower anterior is 20.7 cm.

The neck or most constricted part of the shaft is at a distance of somewhat less than half the length of the bone from its proximal end. Here it has an oval cross section with greater and lesser diameters of 3.5 cm. and 1.8 cm. Because of its slightly convex posterior margin and the remarkable expansion of the distal end of the scapula to a width of 13 cm., the anterior margin is sharply concave.

The glenoid articular surface, of appreciably greater area on the scapula than on the coracoid, is nearly circular with a diameter

of about 4 cm. It is moderately concave and is directed more down than outward. The exceptionally large size of this articulation is accommodated by a slight outward expansion of the postero-proximal corner of the bone and a much greater inward expansion to a total thickness of about 6.2 cm. The length of the articulation with the coracoid is about 7.0 cm., about 2 cm. less than the total antero-posterior measurement of the proximal end.

The plane of the distal expansion is twisted, the anterior corner inward, so as to form an angle of about 15° with that of the proximal end.

THE CORACOID

In comparison with the scapula the coracoid is long and slender. It measures 19.0 cm. along its median line and 20.7 cm. along the greatest diagonal, from the upper anterior to the lower posterior corner. The greatest constriction is somewhat less than a third the length of the bone from its proximal end. Here its cross section is straight on the inner side and sharply convex on the outer side with an antero-posterior diameter of 3.4 cm. and a thickness of 2 cm. In posterior view the coracoid is sharply curved, concave inward in its proximal third, and straight in the distal two-thirds. The distal end is thin and is antero-posteriorly expanded to a width of 9.5 cm. The articular surface in the glenoid fossa is not well represented but seems to have been of considerably less area than that on the scapula. A coracoid foramen of small size pierces the outer surface about half way between the anterior edge and the glenoid and somewhat nearer the upper than the lower edge of this anterior projection. It is directed posteriorly more than inward.

THE INTERCLAVICLE

Little can be said of the interclavicle except that it is spatulate, long and slender, and comparatively thin.

THE PELVIC GIRDLE

All parts of the pelvic girdle are adequately represented. Although much of the bone has been lost by weathering the parts

left, together with the clean cut molds show all the bones in their normal relationships. The pelvis, as a whole, is a little distorted from pressure most conspicuous of which is the likelihood that the anterior end of the pubes is somewhat higher than the position in life. (Figure 3.)

The girdle, in its main features, is typically crocodilian. The acetabulum, excavated chiefly in the ilium, is perforate. The pubis is excluded from the acetabulum and from contact with the ilium. One of the striking features is the large size of the acetabulum. If the specimen has been correctly interpreted the articular surface is not confined to the region of the posterior

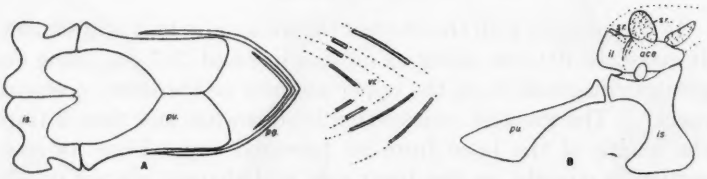


FIG. 3.—*Dakotasuchus kingi* Mehl. Diagrammatic figures of pelvic girdle and ventral ribs, all details about $\frac{1}{4}$ natural size. A—ventral view of pelvis, ischia foreshortened and ilia omitted, showing the relationship of "pubic guard" and the position of ventral ribs. B—left lateral view of pelvis to show development of sacral ribs and pubis.

ischiatic articulation but extends well forward toward the anterior articulation.

THE ILIUM

The ilium of the right side is missing and only part of the left ilium is preserved. Its upper posterior part, probably somewhat less than half of the bone, is missing. In its posterior two-thirds, the section across the acetabulum, it is deeply concave antero-posteriorly. The anterior third is slightly convex. The anterior ischiatic articular surface is a distinct facet produced without conspicuous expansion of the lower edge of the bone. This is separated from the posterior facet by an elongate foramen which is shared equally by ilium and ischium. The antero-posterior diameter of the opening, appreciably less than the vertical diame-

ter, is about 1.5 cm. The posterior ischiatic articulation, nearly three times as long as the anterior articulation, is about 4 cm. and apparently is more than 2 cm. wide. There is no conspicuous expansion of the bone to form this articulation. The articular surfaces seem to lie in the same plane. The total length of the lower end, including the free lower anterior process, is about 5 cm.

THE ISCHIUM

The outlines of both right and left ischia are cleanly impressed in the matrix. Most of the bone has been lost, but the proximal end of the left ischium is nearly complete. The molds indicate that the ischia were united at the median line. The ischium is remarkable because of the relatively great width and strength of its upper end. Measured antero-posteriorly, its width is nearly 9.5 cm. This includes an exceptionally long pubic process that extends anteriorly at right angles to the shaft. The pubic process of the ischium is expanded inward so as to form, with the broadly expanded head of the ischium proper, a large part of the deeply cupped acetabular surface.

The inner edge of the head proper forms the posterior articulation with the ilium. The anterior articulation is formed by a small area of the inner posterior corner of the pubic process. The average thickness of the laterally expanded head and pubic process, measured transversely at right angles to the shaft, is probably about 5.0 cm. The section of the shaft, a third its length below the head, is an antero-posteriorly much elongate oval, 3.2 cm. long and probably not more than 1 cm. wide. Below this section the bone thins rapidly and is greatly expanded antero-posteriorly to a maximum width of 8.5 cm. near the lower end, at right angles to the axis. The greater expansion is toward the front. The total length of the ischium is about 14.5 cm.

THE PUBIS

The proximal half of the left pubis and the distal half of the right are preserved. The clean cut impression of each bone in the matrix adds further data. The pair seems to have been united along the median line at their distal expansion for a distance of about 5.0 cm.

The axis of the pubis is nearly straight. The head is flat in a plane perpendicular to the axis, oval in outline with greater diameter of about 4.2 cm. and lesser diameter of probably not more than 3 cm.

The shaft is sharply constructed to a somewhat lens shaped cross section 2 cm. wide and about 1.5 cm. thick at a distance of 2.5 cm. below the head. Beyond this constriction it thins and is rapidly expanded laterally to a width of nearly 11.0 cm. The thickness at about mid-length of the pubis toward the rounded outer edge is 1.2 cm. The inner edge is moderately sharp. The anterior end is very thin and broadly rounded.

The greatest length, measured along the outer edge, is 17.0 cm. The direct distance from the inner side of the head to the inner anterior corner is 13.2 cm.

SUMMARY OF CONCLUSIONS AND DATA

The specimen here described represents a mature individual. It indicates an average length for this group of between ten and twelve feet, depending on the proportional length of the skull and tail both of which are missing in the type material.

If, as Williston suggested,[2] the broad short scapula is indicative of stout powerful legs, *Dakotasuchus* was probably more at home on the land than in the water. This is in keeping with the comparatively heavy flexo-rigid dermal armor and may well account for the scarcity of remains of this type of crocodilian.

The type material of the genus and species, consisting of a large concretion broken into two pieces, came from the Dakota sandstone a few miles west of Salina, Kansas. In the concretion, preserved either as bony material or natural molds, are represented all parts of the skeleton except the skull, tail, and limbs.

The specimen is preserved in the museum of Kansas Wesleyan University at Salina, Kansas. It was through the kindness of Professor King, former dean of the college, that the writer was permitted to study the material. The species is named in his honor.

[2] Williston, S. W.: The Osteology of the Reptiles. Harvard University Press, p. 140, 1925.

RELATIONSHIPS

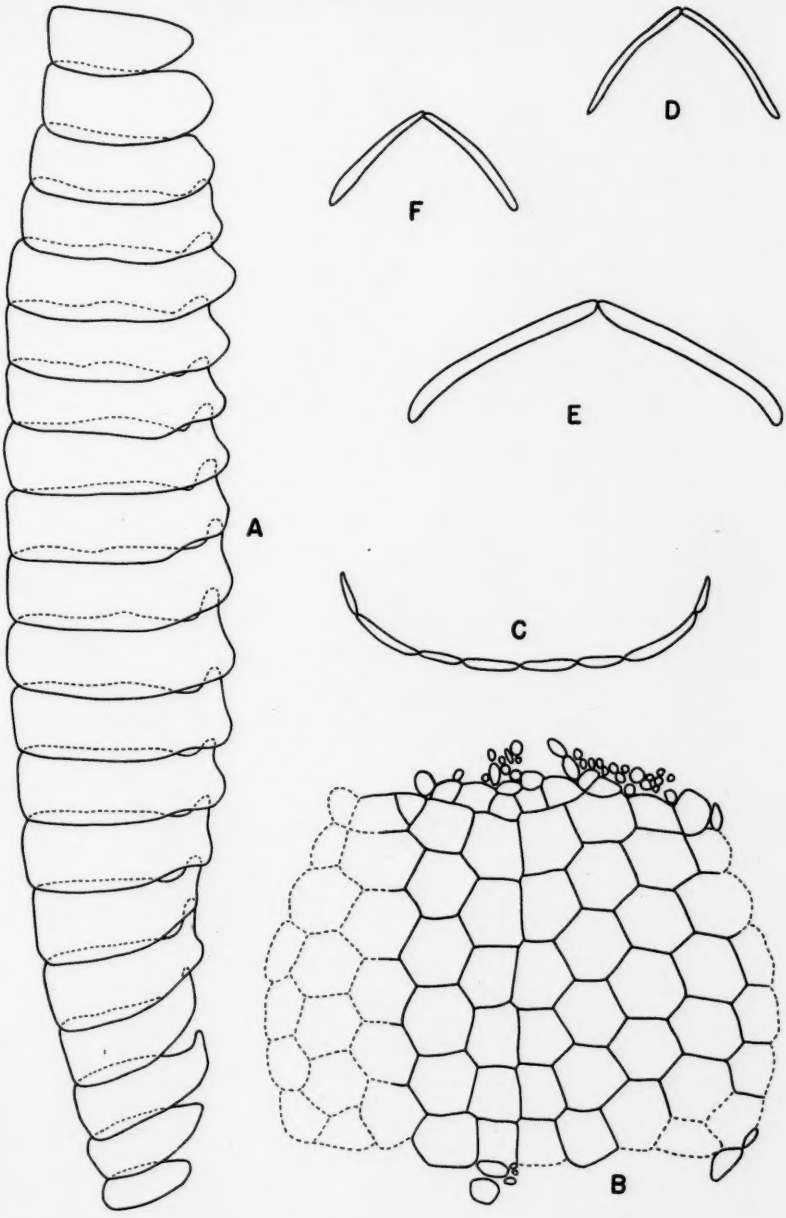
It does not seem profitable, in the absence of other material with which to compare the specimen here described, to state the generic and specific characters of *Dakotasuchus kingi* more definitely than is indicated by the description of the several parts.

In as much as the classification of the Crocodilians is based largely on skull characters the affinities of *Dakotasuchus* must remain highly speculative until the skull of this form is made known. The vertebrae, with only the last dorsal adequately known, seem to be neither typical amphicoelous nor platycoelous, but are probably to be classed as the former. These vertebrae and the heavy complete dermal armor, the dorsal part of which consists of two rows united at the median line, show unmistakable Mesosuchian affinities. For certain family assignment *Dakotasuchus* must await discovery of characteristic skull material.

EXPLANATION OF PLATES AND FIGURES

PLATE II

Dakotasuchus kingi Mehl. Sketches showing details of dorsal and ventral armor, all figures about ½ natural size. A—left lateral view of dorsal plates (anterior end toward the top) with underlap indicated by dotted outlines. B—arrangement of plates of ventral shield (anterior end toward the top) with transverse section, C, at mid-length. D, E, and F are cross sections of plates 1, 9, and 18 respectively, of the dorsal shield.



M. G. MEHL

DAKOTASUCHUS KINGI

Plate III

Dakotasuchus kingi Mehl. Photographs of the concretion containing the type material of the genus and species. A—dorsal view showing the impression and some of the plates of the dorsal armor. B—ventral view showing the impression of the ventral shield and parts of pectoral and pelvic girdles. In each case the anterior end is up. The figures are approximately $\frac{1}{3}$ natural size.

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